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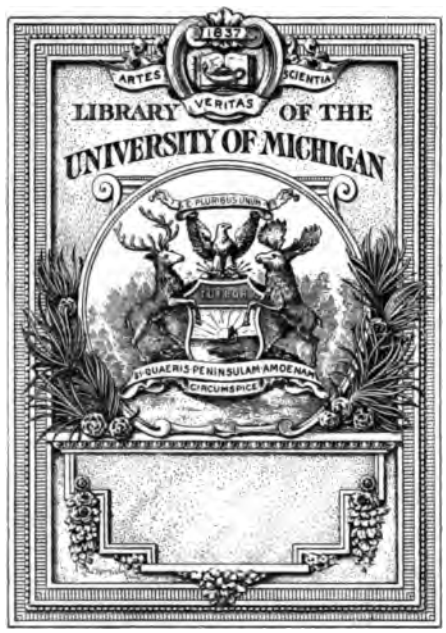

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DEPARTMENT OF THE INTERIOR
UNITED STATES GEOLOGICAL SURVEY
GEORGE OTIS SMITH, DIRECTOR

BULLETINS

Nos. 322-325

WASHINGTON
GOVERNMENT PRINTING OFFICE
1907

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GEOLOGY AND OIL RESOURCES OF THE SANTA MARIA OIL DISTRICT, SANTA BARBARA COUNTY, CAL.

By Ralph Arnold and Robert Anderson.

INTRODUCTION.

PURPOSE OF THIS REPORT.

During the last three years the region near the Pacific coast in the northern part of Santa Barbara County, Cal., has shown promise of becoming one of the most productive oil fields of the West, if not of the whole United States. The developed fields lie on the low, rolling hills between the Santa Maria and Lompoc valleys, where the oil has accumulated in great abundance in the Monterey shale, of middle Tertiary age, which underlies this region. The lightness of the oil, which averages from 25° to 27° Baumé, and the great productiveness of the wells, which yield as high as 3,000 barrels a day, with an average of 300 to 400 barrels, are among the features for which the district has become noted. Large areas in the same general region as the productive fields have been known for some time to be analogous, so far as surface evidence went, to the proved territory, and it was thought that geologic investigations of the region might furnish valuable information and aid in the extension of developments. Accordingly, with the purpose of studying the occurrence of the oil, the extent and structure of the oil-bearing formations, and their relations to associated formations, the writers carried on the field work leading to the present report during the summer and autumn of 1906. The geology of the region covered by the accompanying geologic map (Pl. I, in pocket) has not been completely studied in all parts. Between the San Rafael and Santa Ynez ranges it has been worked with considerable detail, but the mapping of the mountainous regions has been more in the nature of a reconnaissance outside of the areas of the Monterey formation.

A preliminary paper containing the features of this report most immediately pertinent to the oil developments and an outline map has been published as Bulletin No. 317 of the United States Geological Survey.

ACKNOWLEDGMENTS.

Mr. H. R. Johnson covered the territory northeast of the Santa Maria Valley, and the map and notes concerning that region are largely the result of his work. Dr. H. W. Fairbanks[a] is quoted on the geology of Point Sal.

The writers are greatly indebted to Mr. F. J. Keeley and Prof. C. S. Boyer, of Philadelphia, and to Dr. Albert Mann, of the United States Department of Agriculture, for information concerning diatoms and their relation to the origin of the oil. Acknowledgments are also due to Messrs. E. C. Sullivan, W. T. Schaller, and George Steiger for making analyses of the Monterey shale. The analyses of oil on pages 115–117 were made by H. N. Cooper and published by the California State Mining Bureau in its Bulletins Nos. 31 and 32. The indebtedness of the writers to Mr. Cooper and to the mining bureau for this information is hereby acknowledged.

Without the assistance of the operators in the developed field that part of the report which relates to the geology of the wells, production, and other technical data would have been an impossibility, and the writers therefore wish to acknowledge their indebtedness to the officers and managers of the different oil companies for their hearty cooperation and support. Thanks are due more particularly to Mr. W. W. Orcutt, geologist of the Union Oil Company; Messrs. J. F. Goodwin and F. J. Burns, of the Pinal and Brookshire oil companies; Judge John D. Bicknell and Mr. Morris Albee, president and secretary, respectively, of the Western Union Oil Company; Mr. Adolph Phillips, of the Graciosa Oil Company; Mr. W. O. Maxwell, of the Recruit Oil Company; Mr. Charles Off, of the Rice Ranch Oil Company; Mr. E. E. Henderson, of the Palmer Oil Company; Mr. F. D. Hall, of the Hall & Hall Oil Company; Mr. W. A. Irwin, of the Claremont Oil Company; Capt. N. P. Batchelder, of the Los Alamos Oil and Development Company; Mr. Frank M. Anderson, geologist of the Southern Pacific Company; Mr. William Vanderhurst, of the Todos Santos Oil Company; Mr. D. G. Scofield, vice-president of the Standard Oil Company, and many others whose assistance has added materially to the value of this report.

PREVIOUS KNOWLEDGE OF THE GEOLOGY.

Little attention has been given heretofore to the geology of the Santa Maria district. The earliest work was done by Thomas Antisell, with the assistance of observations by Albert H. Campbell, in the course of the explorations and surveys for the Pacific Railroad

[a] The geology of Point Sal: Bull. Dept. Geol., Univ. California, vol. 2, 1896, pp. 1–92.

in the early fifties.[a] In the report on this work the larger topographic features were well described, the presence of asphaltic rocks was briefly noted, and the Tertiary age of most of the sedimentary rocks was recognized, but the structural features and the relations of the rocks were in the main misinterpreted.

During the course of the geological survey of California by J. D. Whitney a hasty reconnaissance was made of a part of this region.[b] He says in his report:

The region to the west of the San Rafael Range, between the Santa Ynez and Cuyamas rivers, was cursorily examined by our party. * * * The region is occupied by hills of moderate height. No metamorphic rock was seen; but pebbles of serpentine and metamorphic sandstone were noticed, especially for 3 or 4 miles north of Alamo Pintado. * * * These hills were covered with gravel derived from the bituminous slates. At times, especially near the Santa Maria River, the hills were capped by a modern horizontal deposit (post-Pliocene?). The underlying rock, when seen, was the bituminous slate, sometimes dipping to the north and sometimes to the south.

Near Foxen's, on the south side of the valley, there were hills of nearly horizontal strata from 200 to 300 feet high, the north slopes of which were very steep, usually about 35°. Beneath the soft sandstone, which made up the principal part of these hills, was a stratum of infusorial rock resembling chalk in appearance, exceedingly light, its specific gravity not being more than 0.6 or 0.7; the thickness of this stratum was over 20 feet. The age of this formation is not yet definitely ascertained.

North of the valley, at Foxen's, the bituminous slate occurs with a high dip to the north, and asphaltum is found in several localities near. In places the slates are altered and silicified, sometimes resembling semiopal in appearance, the finest laminæ of the original structure being preserved.

So far as the writers are aware no further investigation of the geology of the region was made until H. W. Fairbanks made examinations of portions of the Coast Ranges and reported on them for the State mining bureau in 1894. In his paper on the "Geology of northern Ventura, Santa Barbara, San Luis Obispo, Monterey, and San Benito counties" reference is made[c] to the region under discussion, especially to the Santa Ynez Mountains. Regarding the Santa Ynez Range he says: "It is formed, so far as is known, of Miocene rocks exclusively." And again:

There can be no doubt that the main portion of the Santa Ynez Range is Miocene with a general anticlinal structure, well shown in the San Marcos Pass. The center of the anticlinal is not generally the highest portion of the range, but lies on the eastern slope. The normal type of anticlinal structure is also marked by an east and west compression, producing features, however, of secondary importance.

As viewed from the south at various points the range consists of heavy-bedded sandstone, dipping at a high angle to the south. * * * At the western end, in the vicinity of Point Arguello, no anticlinal structure is apparent, but steeply inclined and broken strata. Asphaltum is found in many places near the sea from Point Arguello to Ventura County.

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[a] Pacific R. R. Repts., vol. 7, 1857, Chaps. VIII, IX, and X.

[b] Geological Survey of California, Geology, vol. 1, 1865, pp. 135–138.

[c] Twelfth Ann. Rept. California State Mining Bureau, 1894, pp. 498–506.

The present writers are in agreement with these statements except as regards the exclusively Miocene age of the rocks, a large part of which are here considered as Eocene. On page 505 of Fairbanks's article he speaks of "shales and sandstones of undoubted Cretaceous age" between Gaviota Pass and Santa Ynez River, in the hills which in the present paper are considered as part of the Santa Ynez Range. In the very short time spent in this locality the present writers found no evidence of the presence of Cretaceous rocks.

A number of asphalt deposits in northern Santa Barbara County are described on pages 30 to 33 of the twelfth annual report of the State mineralogist, cited above. The localities mentioned are on the Los Alamos grant, 4½ miles north of Harris station; along the northern slope of the hills bordering the Santa Maria Valley, 10 miles southeast of Santa Maria; about 2 miles northeast of the Purisima Mission; along the southern slope of the hills between the Los Alamos and Santa Ynez valleys (Purisima Hills), especially on the San Carlos de Jonata grant; and in poorer and less known deposits at Gaviota Landing, at Point Arguello, near the mouth of Canada Honda, and at other points toward Lompoc Landing. Seepages out of the bituminous "slate" (shale) series are mentioned as occurring in the canyon of the Sisquoc, about in the center of the Sisquoc grant, along Labrea Creek, and near the west end of the Tinaquaic grant.

By far the best observations recorded up to 1896 regarding the geology of this region were those of H. W. Fairbanks, published in his paper on the "Geology of Point Sal."[a] He gives a detailed description of the igneous and sedimentary formations occurring at the seaward end of the hills, termed in the present report the Casmalia Hills. In speaking of the even summit line of the Point Sal Ridge he says:

> The regularity is due, in part at least, to the fact that the strata on the summit are nearly flat and composed of the resistant Miocene flints, while on the southern slope the bituminous shales are followed in descending order by a great thickness of gypsiferous clays, in which broad valleys have been eroded. Lower down toward the ocean the clays are replaced by strata of volcanic ash, sandstone, and conglomerate, in which, because of their greater resistance, canyons have been eroded. The strata of volcanic ash form very striking features in the landscape on the lower slopes of the ridge; being interbedded with soft clays they weather out in cliffs and projecting ridges.

In outlining the geology of the region of Point Sal Ridge, Fairbanks says:

> The region about the point itself has been the scene of many violent disturbances and repeated eruptions of basic magmas. A part of these consolidated as surface flows, while others have the characters of deep-seated rocks.
>
> The sedimentary strata comprise only the Pleistocene, Miocene, and Knoxville. * * * The Miocene is the most extensive formation represented. * * * It is

[a] Bull. Dept. Geology Univ. California, vol. 2, No. 1, 1896, pp. 1-92.

divisible into two distinct parts—the upper, the bituminous shales, and the lower, the gypsiferous clays. Below the clays are sandstone, shales, and conglomerates resting on the gabbro and serpentine. * * * The strata of volcanic ash appear in the lower Miocene beds. There are three distinct horizons, the lowest resting on the gabbro.

The igneous rocks are treated in especial detail in this paper and a very good description is given of the bituminous shales. The conclusions of the present writers are in agreement with the statements above quoted and the others contained in Fairbanks's paper.

In 1901 George H. Eldridge gave an admirable general outline of the topography and geology of the country surrounding the Santa Maria field in his treatise on "The asphalt and bituminous-rock deposits of the United States," and discussed in detail its asphalt deposits.[a] He says:

The geology of the region embraces an underlying series of folded Monterey shale of both the soft and more organic material and that which is hard and siliceous, but the former predominates. So far as observed by the writer this series of beds was not exposed at any point in its entirety. Overlying the Monterey unconformably, and especially developed in La Graciosa Hills, is the heavy and extensive deposit of Pliocene sands, grits, and conglomerate already referred to. The composition of the later deposit is chiefly quartzose.

Eldridge "observed a prevailing central fold somewhat to the north of the topographic axis of the ridge" south of Waldorf, in the Casmalia Hills, this being no doubt the fold described in the present report as the Schumann anticline. He says further:

The Pliocene * * * shows a less degree of folding than the underlying Monterey, yet the movement that produced the pre-Pliocene ridge has apparently been continued subsequent to the deposition of the materials of this age, for gentle dips of from 2° to 10° are to be observed in the later formation.

In discussing the country east of Los Alamos, between the San Rafael Range and the Santa Ynez Valley, which he calls the Los Alamos region, Eldridge says:

In structure the Los Alamos region presents a series of folds which are in general coincident with the topographic ridges and valleys. * * * It is worthy of note that the valleys of the region under consideration for the most part occupy the synclinal troughs. It is possible that some of them also occupy fault lines. * * * The general trend of the folds for the Los Alamos district, and indeed for a great stretch of country beyond, is N. 70° to 80° W., the dips being north and south. Excepting in their trend, however, there is but little regularity in the disposition of the folds, and their axes, both longitudinal and transverse, vary greatly in length. In addition to the main and conspicuous folding that has been described, there are frequent crumples of minor importance.

In another place Eldridge mentions a lens of limestone included in the serpentine in a high bluff just north of Alamo Pintado Creek, along the old beach line where the Fernando was deposited upon the Franciscan at the base of the San Rafael Mountains. This lime-

[a] Twenty-second Ann. Rept. U. S. Geol. Survey, pt. 1, 1901, pp. 424-441.

stone was composed largely of Pliocene shells, as determined by Doctor Dall. Eldridge remarks: "In view of the supposed age of the serpentine, it is thought that the deposit was formed by the accumulation of sediment and shells in a crevice of the older rocks at the time they perhaps formed the sea bluffs."

The same writer published a brief summary of his knowledge concerning the Santa Maria district in 1903.[a]

The San Luis folio,[b] by H. W. Fairbanks, issued in 1904, contains much that relates to the district in general, although it pertains directly only to the part containing the Arroyo Grande field. It is the most comprehensive report concerning the northwestern part of the Santa Maria district yet published.

The present writers have published two papers concerning the geology and economic resources of the Santa Maria district. The first is entitled "Diatomaceous deposits of northern Santa Barbara County, Cal.,"[c] and the second "Preliminary report on the Santa Maria oil district, Santa Barbara County, Cal."[d] A third paper treating more in detail the burning of the shale is "Metamorphism by combustion of the hydrocarbons in the oil-bearing shale of California," to be published in the Journal of Geology.

EARLY HISTORY OF THE DISTRICT.

The Santa Maria district was up to 1899 entirely unknown as an oil-producing territory. To Messrs. McKay and Mulholland, of Los Angeles, is due the credit for starting operations in the Santa Maria field proper. After a favorable report had been made by Mr. Mulholland on certain lands of the Careaga ranch, the Western Union Oil Company was organized, drilled three prospect holes, and was finally rewarded in August, 1901, by striking paying quantities of oil in the third well. In 1902 the Pinal Oil Company, of Santa Maria, began operations on the north side of Graciosa Ridge, and meeting with marked success was followed by the many other companies that have since undertaken operations in this field.

Successful wells were drilled in the Lompoc field in 1904, and since that time the further development of this part of the district has been assured. A later field to attract attention is that adjacent to the town of Arroyo Grande, where development is well under way, being stimulated by the completion of the successful Tiber well No. 1 late in 1905. Prospecting is now (January, 1907) going forward in the Huasna field east of the Arroyo Grande field, and the operators there confidently expect to develop productive wells.

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[a] Contributions to economic geology, 1902: Bull. U. S. Geol. Survey No. 213, 1903, p. 313.
[b] Geologic Atlas U. S., folio 101, U. S. Geol. Survey, 1904.
[c] Bull. U. S. Geol Survey No. 315, 1907, pp. 438-447.
[d] Bull. U. S. Geol. Survey No. 317, 1907, pp. 1-69, 2 pls., 1 fig.

GEOGRAPHY AND TOPOGRAPHY.

LOCATION.

The region discussed in this paper is situated on the California coast in Santa Barbara County, between 120° and 120° 40′ west longitude and 34° 30′ and 35° north latitude. In areal extent it is about 1,300 square miles and it practically covers the Lompoc and Guadalupe quadrangles as topographically mapped by the United States Geological Survey. It includes portions of the San Rafael and Santa Ynez divisions of the Coast Ranges and the basin region lying between them, which is occupied by the Santa Maria, Los Alamos, and Santa Ynez valleys and the intervening hill ranges. It is bordered on the north by the San Luis Obispo County line, on the west and south by the Pacific Ocean, and on the east by the Santa Ynez quadrangle, which covers the high, wild mountains north of Santa Barbara. On its west coast are Point Sal and Point Arguello, and the south coast includes Point Conception and part of the long, straight shore line that runs due east from that point toward Santa Barbara. These are among the most prominent coastal features of California.

The region is thoroughly intersected by roads, except in some of the uninhabited portions. The Southern Pacific Railroad coast line, part of the transcontinental system, extends close to the ocean entirely around two sides of the area, and the Pacific Coast Railroad, a local line from Port Harford and San Luis Obispo, runs into the region as far as Los Olivos via Santa Maria. A rough estimate would place the number of inhabitants of this region between 5,000 and 10,000.

The Arroyo Grande and Huasna oil fields, in the San Luis quadrangle, San Luis Obispo County, are also briefly mentioned, although not a part of the region whose general features are described in this report.

DEFINITIONS OF PLACE NAMES.

The following list defines certain place names as used on the map and in this report. The two main mountain ranges have heretofore been indefinitely designated The other names are newly applied.

The only land comprised within the Guadalupe quadrangle is the narrow strip of coast west of longitude 120° 30′ W. The Lompoc quadrangle covers the rest of the area shown on the map east of that line.

The San Rafael Mountains include the whole group between Santa Ynez and Cuyama rivers.

The Santa Ynez Mountains include the whole range east of Point Arguello between Santa Ynez River and the ocean.

The Casmalia Hills include the group extending from the coast at Point Sal to Graciosa and Harris canyons and San Antonio Valley.

The Solomon Hills lie between the Santa Maria Valley, Foxen Canyon, and the Los Alamos Valley, and between Divide and La Zaca Creek.

The Purisima Hills lie between Lompoc, the Santa Rita Valley, and the Santa Ynez Valley on the south and the Los Alamos Valley on the north, and between Burton Mesa on the west and Alamo Pintado Creek on the east.

The Santa Rita Hills lie between the Santa Ynez and Santa Rita valleys, extending from a point east of Lompoc nearly to the east edge of the Santa Rosa grant.

The name San Antonio terrace is applied to the wide terraced region between Casmalia and the west end of the Los Alamos Valley.

The Lompoc terrace is the plateau-like region of hills extending from the coast a distance of about 5 miles east from Honda and the same distance southeast from Surf.

In 1896 H. W. Fairbanks used the names "Point Sal Ridge" for the axis of the hills between Mount Lospe and Point Sal, and "Lions Head" for a high, rugged mass of serpentine on the coast south of Point Sal. These features are so named here.

RELIEF.

GENERAL STATEMENT.

The general character of the region covered by the Lompoc and Guadalupe quadrangles is that of a triangular hilly basin opening out toward the coast between two divergent ranges of mountains—the San Rafael Range in the northeast portion of the area and the Santa Ynez Range bordering it on the south. At the east edge of the area mapped these ranges are divided only by the valley of Santa Ynez River and the foothills north of it. Farther west the distance between them grows to 30 miles or more. The region situated in this angle is primarily a basin, owing its character and the details of its structure to its position between these ranges. This basin region, its structure, and its oil deposits form the principal subjects of discussion in the present paper.

Two lines of hills and three valleys occupy this trough between the two main ranges, radiating like the intermediate ribs of a fan between the lines that bound them. The more northerly of the two lines of hills is that of the Solomon and Casmalia hills, which are separated from the San Rafael Mountains by the wide valley of Santa Maria River. The more southerly is the range of the Purisima Hills, which is separated from the Santa Ynez Mountains by Santa Ynez River. These two lines of hills are themselves divided by Los Alamos Valley.

They are topographically and structurally young ranges, except the Casmalia Hills, at the extremity of the northern line, which have the character of a separate and old range.

SAN RAFAEL MOUNTAINS.

The most prominent topographic feature is the great mass of the San Rafael Mountains on the northeast and east, 25 to 30 miles back from the ocean. The structural trend of the range is N. 50° W., approximately parallel with the general course of the lines of structure in California, although on the whole more westerly. The range runs obliquely to the north-south coast line west of it, but farther north, where the Santa Lucia Range, its northward continuation, approaches the ocean the coast curves to the northwest under the control of the mountains.

Although the portion of the San Rafael Range included within the area shown on Pl. I (pocket) composes a high, rugged maze of ridges reaching elevations that range between 2,000 and 4,300 feet, this portion is in the larger aspect, but subsidary to the main mountain group farther east, in which altitudes approaching 9,000 feet are attained. The ridges are divided by steep canyons, most of which cut transversely across the formations regardless of the folding and structural lines. Rounded soil-covered slopes form a considerable portion of the part of this range included in the Lompoc quadrangle, but rough, rocky slopes are likewise abundant. The range is traversed centrally by the well-graded canyon of Sisquoc River, which divides it into two mountain groups. On the south and north the range is bounded by wider graded valleys—those of Santa Ynez and Cuyama rivers. The Santa Ynez divides two distinct ranges. The Cuyama forms a more arbitrary division in the Coast Ranges. Near its mouth, at the point where it reaches the area included in the accompanying map, it veers to the south and cuts a narrow gorge across the San Rafael Mountains without regard to the structure. The range may be regarded as continuous across this portion of the river.

Within the triangular area mapped the high ridges and mountains around Zaca Lake, Bone Mountain, Tepusquet Peak, and Los Coches Mountain are boldly defined, with steep side slopes descending into narrow canyons, and as a rule rounded summits. The broad ridge originating north of Los Coches Mountain and extending southeastward to North Fork of Labrea Creek, where its character is temporarily lost until it appears again in Manzanita Mountain, is a striking feature with its long southwestern and abrupt northeastern slopes. The seaward flanks of the range terminate rather abruptly in the terraces bordering the Santa Maria Valley.

SANTA YNEZ MOUNTAINS.

The Santa Ynez Mountains form a long, narrow range bordering the Santa Barbara Channel and bounded on the north by the westward flowing Santa Ynez River. The trend of the range is east and west and has determined the unusual direction taken by the coast south of it. The range is about 9 miles in average width and contains two lengthwise zones. The southern zone comprises a ridge with remarkably even sky line, which rises directly from the sea. This ridge increases in height toward the east from an elevation of 1,000 feet at Point Conception to 3,800 feet east of Refugio Pass and more beyond the boundary of the area mapped. At Point Conception the coast bends abruptly to the northwest around the end of this ridge, but north of Jalama Creek a similar ridge, that of the mountain El Tranquillon, follows the coast as far as Point Arguello, where the shore bends again abruptly and assumes a northward course. The second zone lies between these two coast ridges and Santa Ynez River. It has more the nature of a foothill region, forming a partly individual range of hills and ridges separated from the coastal ridge by longitudinal valleys. The average slope from the summit of the range down to the sea is at an angle of 20° to 30°. In places the angle is less, but on some individual slopes it is greater. The width of the range on the north of the summit ridge is greater and the slope more gentle and more broken than on the southern abrupt slope to the sea. Viewed from the ocean on the south the range has the appearance of a steep, even-topped breastwork; from the north it appears as a belt of discontinuous hills and ridges grouped in front of and almost hiding the long culminating ridge. The Santa Ynez Range forms the most prominent elbow on the California coast.

The topography of this range reflects the structure more than does that of the San Rafael Mountains, and deformation within it does not appear to have gone so far.

In the high mountainous region east of the area mapped, north of Santa Barbara and south of the south end of the great central valley of California, centering at Mount Pinos, lies the point of convergence of all the ranges of mountains in this part of California—the Santa Ynez Range coming in from the west; the San Rafael Range from the northwest; the Santa Lucia and San Jose ranges from the country north of Cuyama River; the Mount Diablo Range, or easternmost member of the Coast Ranges, from still farther north of west; the Tehachapi Range, running southwestward from the south end of the Sierra Nevada; and the San Gabriel Range, which comes from the southeast as the continuation of the Coast Ranges in southern California. Here the northwest-southeast lines of structure, dominant throughout the major part of the State, are met

and opposed by the east-west structure of the Santa Ynez Range, and the result is this convergence of ranges with the consequent formation of a high, structurally complex region. The Lompoc quadrangle is on the western outskirts of this region, and the lines of relief corresponding to the two lines of structure are here beginning to diverge and show their individuality in the two bounding ranges.

SANTA MARIA VALLEY.

Santa Maria River, which takes its rise in two profound valleys within the San Rafael Range, flows along the foot of this range at the north edge of the Santa Maria Valley. This valley is a wide flood plain with an even cultivated floor, surrounded by low terraces that fringe the base of the mountains on the northeast and rise into the Solomon Hills on the south. It opens out to the sea and forms the southern part of the low region lying between Pismo Beach in San Luis Obispo County and the Casmalia Hills.

CASMALIA HILLS.

The most prominent feature of the landscape south of the Santa Maria Valley is a long ridge with a level sky line running northwestward out to the ocean at Point Sal. This is the high ridge of the Casmalia Hills, which rises abruptly from the Santa Maria Valley. Its highest point is Mount Lospe, 1,624 feet above the sea. The slope up to this ridge from the valley on the northeast is steep, but on the north the rise is more gradual over wide slopes of dune sand. On the southeast the ridge declines as it approaches Schumann Pass, the low divide over which the railroad crosses from the Santa Maria Valley to Schumann Canyon; on the south it forks into successive ridges which slope gradually into terraced hilltops bordering Schumann Canyon; on the west it drops off abruptly into steep, rocky declivities that fringe the sea in the neighborhood of Point Sal. The ridges continue southeastward opposite Schumann Pass as far as Graciosa Canyon, where they sink under more recent sand formations and lose their character. South of Schumann Canyon the terraced slope continues in the San Antonio terrace as a wide plateau locally intersected by sharply defined U-shaped canyons. The Casmalia Hills, particularly that portion north of Schumann Canyon, have a distinct individuality among the topographic features of the basin region, and may be regarded as a separate although small range allied in age and character with the bounding ranges. It is conformable in trend with the San Rafael Mountains and forms a prominent headland jutting out to sea.

Most of the ridges in these hills follow the strike of the beds. Their summits are characteristically of gentle incline; the side slopes

range from gentle to fairly steep, being in many places determined by the dip. Pl. IX, *A* (p. 80) shows excellent examples of the strike ridges, dip slopes, and even sky lines of these hills. The ridges diverging from Mount Lospe are given prominence by the hard flint of which they are formed, and the sharp outlines of the slopes along the coast southward from Point Sal are caused by the resistant igneous rocks there exposed.

South of the Casmalia Hills the sea has cut into soft formations and along structural lines, so as to leave the Point Sal Ridge jutting out as a promontory. The same is true on a smaller scale south of Purisima Point, the seaward extension of Burton Mesa, and south of the west end of the Santa Ynez Range. The coast north of each of these headlands runs northward, with only a gentle curve away from the point, until the indentation south of the next range is reached. The east-west coast lines follow structural features; the north-south lines truncate them. Faults are not concerned in any of the north-south features along this part of the coast.

North of the Casmalia Hills the coast forms a straight north-south line bordering the lowland that opens out at the mouth of the Santa Maria Valley as far as the deep indentation at the base of the San Luis Range, which exhibits the best example of this type of coastal structure. The latter range lies in the San Luis quadrangle and has been described in the folio covering that region.[a]

SOLOMON HILLS.

Although the Casmalia Hills drop into insignificance in the vicinity of Graciosa and Harris canyons, their general line of topographic relief continues with a more easterly course toward the San Rafael Mountains, the whole being in fact a spur of this range. The Solomon Hills are a group of low, rolling hills covering a wide area between the Santa Maria and Los Alamos valleys. From a distance the area looks like an undulating plateau sloping away on all sides except the east to wide, slightly inclined or flat valleys.

The features of the topography of the Solomon Hills are shown in Pl. XI (p. 98). From a point near at hand the individual hills and valleys of irregular round and square forms assume bold outlines. The angular slope of hills capped with low-dipping beds of sand and having steep, squarish flanks is very characteristic of the region. Many ridges have fairly flat summits, which slope gently, with a long, even sky line, and are due to surface cappings of sand hardened by iron oxide. Such a capping has in places the appearance of a resistant bed forming the ridge top and determining the slope by its low dip.

Mount Solomon has an elevation of 1,338 feet and other peaks rise

[a] Geologic Atlas U. S., folio 101, U. S. Geol. Survey, 1904.

as high as 1,600 feet. A common height for summits in these hills is 1,200 feet.

Wide, shallow, filled valleys between the rolling summits are characteristic of the Solomon Hills, the soft valley filling being as a rule sharply cut along a meandering course by a miniature stream gorge that has been rapidly eroded. Many of these recent channels are deeper than they are wide. In the vicinity of La Zaca Creek on the east the Solomon Hills merge with these foothills, and the general topographic features are continued in them. The Solomon Hills owe their low outlines largely to their structural development rather than to their topographic maturity. It has been an area of building up as well as of wearing away, and the original topography, which reflected characteristically the folds of the sedimentary formations, has been obscured by further deposition and by the filling of valleys, in addition to alteration by erosion.

LOS ALAMOS VALLEY.

The incline of the Solomon Hills on the south is gradual down to the Los Alamos Valley. This valley extends from the region where the Solomon and Purisima hills coalesce in the foothills of the San Rafael Range a distance of about 27 miles to the coast, in a direction about N. 75° W. This, it will be noted, is much more westerly than the trend of the Santa Maria Valley. The Los Alamos Valley separates the two basin ranges—the Solomon and Purisima hills—and is a drainage feature of them alone. The average altitude at the summit of its watershed is from 1,000 to 1,300 feet; and the highest elevation that the watershed reaches anywhere is less than 2,000 feet. All the water from the higher surrounding regions that drains into the Santa Maria basin region escapes either into the Santa Maria Valley on the north or the Santa Ynez Valley on the south.

PURISIMA HILLS.

The second of the two hill ranges is that of the Purisima Hills, which forms a definitely outlined structural and topographic unit springing from the plateau region about Santa Ynez and the foothills of the San Rafael Range in the vertex of the triangular basin. It rises at that point in the shape of a number of strike ridges which run northwestward and then curve around to the west, coming together. For most of the distance to the ocean beyond this junction the range consists of a single ridge running parallel to the Los Alamos Valley. On the north it sends out lateral ridges that drop off rather abruptly into the Los Alamos Valley. These ridges are separated by fairly sharp V-shaped valleys, although some of the valleys have sides of more gentle slope and filled bottoms. A striking topographic feature is a

longitudinal trough running for miles parallel with this range and the Los Alamos Valley and cutting across the ends of the above-mentioned ridges at right angles to them, at a distance of one-half to 1 mile from the valley. It notches all the ridges and leaves an individual row of knobs 100 to 200 feet in relief bordering the valley. This depression is not a continuous drainage feature, but is stratigraphically of importance as approximately marking the contact between the Monterey shale and the loose Fernando sand. On the south side of the summit of the Purisima Hills the lateral ridges extend a long way with a uniform gentle slope, like remnants of an eroded inclined plateau. At their base, some miles from the summit, and usually from 500 to 1,000 feet below, these southern slopes merge into an undulating hilly plateau that has the appearance of being buried under soft recent sand. The range is broadest at the east end, where it consists of a number of parallel ridges. The point of convergence of some of these is Redrock Mountain, which is 1,968 feet high and the highest summit in these hills. Thence westward the hilly zone narrows into a single central ridge and its offshoots, and gradually pinches out, finally giving place on the south and west to a broad terrace in which its hilly character is lost. The summit of the main ridge of the Purisima Hills west of Redrock Mountain gradually declines in height and for most of the way it is remarkably even, the elevation varying between 1,200 and 1,000 feet. At the elevation of 1,000 feet it grades into the smooth terrace called Burton Mesa.

BURTON MESA.

Burton Mesa is a marine terrace covering more than 50 square miles, which slopes, with an average gradient of 2½ per cent, away from the west end of the Purisima Hills, reaching the sea within 7½ miles. It is composed of Monterey shale, in the main rather gently folded, which has been planed off and covered with a thickness of about 25 feet of horizontal gravel and loose sand. From the elevation of 1,000 feet, where the continuous sheet of sand overlaps on the end of the Purisima ridge, down to the 600-foot level the distance in a west-southwest direction is three-fourths of a mile and the slope 10 per cent. Within the next three-fourths of a mile a drop of 100 feet occurs, the slope being 2½ per cent. Beyond lies the main level stretch of the plateau for a distance of 5 miles, with no greater slope than three-fourths of 1 per cent until the elevation of 300 feet is reached, in the southwest corner of the mesa, where there is an abrupt change to a 10 per cent slope, the distance down to elevation 100 feet being only one-third of a mile. Below the 100-foot level there is a bench with a 3 per cent grade as far as the edge of the cliff which faces the sea, and which is in most places about 25 feet above the water. North

of Canada Tortuga the steeper portion above the coastal bench is only 100 feet high, and in the northwest corner of the mesa the main terrace and the coastal bench grade into each other and become practically one.

SANTA YNEZ VALLEY AND SANTA RITA HILLS.

Santa Ynez River is the second of the two main drainage lines of the area, Los Alamos Creek, the next in size, being much subordinate to these two. The Santa Ynez rises in the high region north of Santa Barbara and flows westward between the Santa Ynez and San Rafael ranges. From the east edge of the Lompoc quadrangle, where these two ranges diverge, it flows slightly to the north of west, at the foot of the Santa Ynez Mountains. Its course is even more westerly than that of the Los Alamos Valley until it approaches the ocean, where the nose of the Santa Ynez Range, as in the two ranges farther north, shows a tendency to change its orientation into greater conformity with the northwesterly course of the San Rafael Range.

This stream has a low gradient of only one-fourth of 1 per cent. Its valley has a steep side on the south formed by the hills of the Santa Ynez Range, but it is widened on the north by the easy slopes of terraces and sand hills, except at the Santa Rita Hills, which rise midway in the river's course.

The Santa Rita Hills form a small separate range reaching a height of 1,300 feet and resembling in miniature the Purisima Hills. The range starts from the valley in several strike ridges running northwest, which join in the highest part of the range and then continue due west as a single ridge. The river follows a tortuous course between this and the Santa Ynez Range and has cut cliffs in many places. On the north the Santa Rita Hills are divided from the Purisima Hills by the Santa Rita Valley, a low basin similar to some portions of the Santa Ynez Valley.

The level floor of the river valley, including the stream bed and the somewhat higher terrace-like flats on either side, ranges in width from a few hundred feet to about a mile until within 10 miles of the ocean, where it opens out into the Lompoc Valley, an alluvial flat several miles wide.

TERRACED COAST.

Pleistocene terraces border the coast for the greater part of the distance around the Guadalupe and Lompoc quadrangles. The great Burton Mesa terrace has already been mentioned. Beyond the valleys to the north and south of this mesa similar terraced areas extend widely and in places to a considerable distance inland, but nowhere else with so gentle a slope as is exhibited on the Burton Mesa.

Where steep hills descend toward the coast there is almost without exception a coastal terrace starting at the top of the sea cliff, which, as a rule, ranges in height from a few feet to more than 50 feet above the water. Most of these terraces extend up to an elevation greater than 200 feet. Some of them have left traces at a height of 300 feet or more, and others continue perfect to this altitude or even higher.

GENERAL TOPOGRAPHIC FEATURES.

The point of especial interest in the topography of the central region between the two bounding ranges is its characteristic reflection of the structure of the formations, whereas in the mountains, as has been noted, the topographic development has been less in accordance with the lines of structure. An anticline in the central region is apt to be coincident with a ridge, as, for example, in the long ridge of the Purisima Hills, which lies close to the axis of a broad anticline. Moreover, some of the larger valleys mark the synclinal axes of the broad lines of structure—a statement illustrated by the Santa Ynez Valley in parts and by its structural, although not actual, continuation in the Santa Rita Valley. It is also exemplified by the upper portion of the Los Alamos Valley and by Harris Canyon. These topographic features may be accounted for by the facts that the main movements in these hill ranges have been gentle as compared with those in the older mountain masses, that the disturbances giving them form have been comparatively recent, and that deformation has not gone so very far. Wherever there are low areas of rolling hills it is almost sure to be found that a syncline or plunging fold has given rise to structural depressions in which deposits of soft sand producing low topographic forms have been laid down.

The character of the different formations shows its influence on the topography. The areas of serpentine with associated Franciscan rocks have irregular broken surfaces with many outcrops and usually an old, well-worn appearance. The dominantly sandstone and shale terranes described under the headings "pre-Monterey rocks" and "Vaqueros, Sespe, and Tejon formations, undifferentiated," do not give rise to a very distinctive topography. They form a succession of ridges and V-shaped canyons of moderate relief and comparative regularity. In many places the truncated edges of the tilted strata form steep, rough strike slopes. The Monterey shale produces the forms of highest relief in this region, as well as forms of low relief, according to the amount of folding that has taken place in it and to its hardness. The brittle shale closely folded gives rise to sharp ridges, many of them serrate, with steep, rocky flanks. Ridges of highly tilted shale are shown in Pl. VI, *B* (p. 46). The lower folds produce hills of gentle incline and long unbroken ridges, in places parallel with the strike

and having a dip slope, as shown in Pl. IX, *A* (p. 80). Characteristic of the soft shale are hills having the form of mounds with symmetrical rounded contours and with few prominent outcrops except pavements of shale forming the surface. The soft Fernando sands form small hills that look like irregular sand piles, and long slopes with shallow erosion features. Some of these slopes reflect the dip of the strata on the flanks of low folds and are structurally inclined plateaus in a typical state of youthful dissection. The valleys are, in many places, filled with sand that has shifted down from the hills faster than it could be carried away by agencies of transportation. Great cliffs of soft sand are common as the result of the rapid undermining and removal of portions of hills. Thus walled cirques are formed. Harder materials in the Fernando cause squarish forms, such as that of Mount Solomon. The terraces of the Quaternary give a strong individuality to the topography of this region. They are widely in evidence along the coast, in valleys, at all levels up to 1,200 or 1,400 feet on slopes, on hilltops, and along horizon lines.

DRAINAGE AND RAINFALL.

The three principal streams have received mention under the previous headings. A small amount of water runs in them all the year round, but the quantity is only rarely sufficient in either of the two main streams to warrant their being called rivers. This name is applied to them on the ground of the importance of their drainage areas. Almost all the drainage of the two quadrangles flows into these three streams. In the main they run parallel to the strike of the formations. In addition to those already mentioned, others that run independently into the sea are Casmalia Creek, in Schumann Canyon, which first cuts obliquely across the end of the Casmalia Hills and then assumes a longitudinal course; Canada Honda Creek and Jalama Creek, the two last having deeply cut courses parallel with the structural lines at the west end of the Santa Ynez Mountains. The steep seaward slope of these mountains is cut into by a great number of short, steep, transverse gorges.

The portion of the San Rafael Range lying within the area covered by the map is drained principally by Sisquoc and Cuyama rivers, which flow along well-graded courses, and by the minor streams, Labrea and Tepusquet creeks. With the exception of the Cuyama, these watercourses and the majority of the others in the mountains have cut transverse canyons across the formations regardless of the folding and the structural lines. In this respect they differ from the streams farther south.

On the whole, it is rather a dry region. An average of only 12 or 15 inches of rain falls annually, during the winter rainy season. During

the long dry season almost complete evaporation of surface moisture takes place, and there is little erosion through the aid of water. Throughout the latter part of the Quaternary period the rate of erosion has probably been slow.

CLIMATE AND VEGETATION.

The climate of this area is that of the coastal region of California. It is equable the whole year round, excessive heat or cold being very rare. The days are mild, the nights chilly. The region is subject to the inroads of heavy fogs and driving winds from the open ocean, but this is true to a lesser degree in the eastern angle of the basin, where there are protecting hills on all sides. The winds blow very strongly from the west and northwest up the radiating valleys that open to the coast. The region is subject to earthquakes, some of which would seem to be of local origin.

The vegetation in the northern part of Santa Barbara County is open, as in the neighboring portions of California. There are almost no dense groves of trees, most of the hills being sparsely clothed with a scattering growth of small trees, usually live and white oaks, and bushes, or else entirely bare, except for sagebrush and grass. The wide terraces and hills of soft sand are commonly overgrown with so-called tarweed and are otherwise almost bare. In the valleys near the coast grow many willows; in the more protected valleys farther inland thrive large sycamores, cottonwoods, and live and white oaks. The steep slopes of the San Rafael Range are sparsely set with small oaks, pines, and yuccas, and, like those of the Santa Ynez Range, are covered in parts by dense thickets of undergrowth.

The vegetation of the hill ranges of the basin region is typically illustrated by Pl. IX (p. 80) and of the San Rafael Mountain region by Pl. VI (p. 46).

GEOLOGY.

SEDIMENTARY FORMATIONS.

GENERAL STATEMENT.

The formations involved in the geology of this district (see Pl. II) include the Franciscan (Jurassic?); Knoxville (lower Cretaceous); pre-Monterey rocks (which may include both Cretaceous and older Tertiary); Tejon, Sespe, and Vaqueros, undifferentiated (Eocene-Miocene); Monterey (middle Miocene); Fernando (Miocene-Pliocene-Pleistocene); and Quaternary. The maximum known thickness of the Tertiary and early Quaternary formations combined is 13,200 feet. The following table shows the correlation of these formations with the

standard California section and with that of Santa Clara Valley, Ventura County:

Tentative correlation of formations of Santa Maria district with the standard California Coast Range section and with that of the Santa Clara Valley.

Era.	System.	Period.	Standard Coast Range section.	Santa Maria district section.	Santa Clara Valley section.
Cenozoic.	Quaternary.	Recent.	Alluvium.	Alluvium.	Alluvium.
		Pleistocene.	San Pedro.	Terrace deposits and dune sand.	Sand and gravel.
			—— Unconformity ——	—— Unconformity ——	—— Unconformity ——
	Tertiary.	Pliocene.	Merced.		
			Purisima.	Fernando.	Fernando.
		Miocene.	San Pablo.		
			—— Unconformity ——	—— Unconformity ——	—— Unconformity ——
			Monterey.	Monterey.	Modelo. {Shale. Upper sandstone. Shale. Lower sandstone.
			Vaqueros.	Vaqueros, Sespe, and Tejon, undifferentiated (including some Monterey in Santa Ynez Range).	Vaqueros.
		Oligocene.	San Lorenzo.		Sespe. {Upper. Red beds. Lower.
			—— Unconformity? ——		
		Eocene.	Tejon.		Topatopa.
			Martinez.		
Mesozoic.	Cretaceous.		—— Unconformity? ——		
			Chico.		
			—— Unconformity ——	(?)	(?)
			Horsetown.		
			—— Unconformity ——		
			Knoxville.	Knoxville.	
			—— Unconformity ——		
	Jurassic (?).		Franciscan.	Franciscan.	
			—— Unconformity ——		—— Unconformity ——
			Granite, schist, etc.		Granite, gneiss, etc.

FRANCISCAN FORMATION (JURASSIC?).

The oldest rocks within the Santa Maria district belong to the Franciscan formation, which is probably of Jurassic age. H. W. Fairbanks described the same formation under the name San Luis in the San Luis folio. The Franciscan is a very important basement formation in the Coast Ranges farther north. The small areas of these rocks occurring here consist of remnants of beds of sandstone, shale, glaucophane schist, and jasper associated with serpentine that has probably been intrusive in them. The sandstone is usually of a dark-green color, fairly fine grained, and considerably indurated. The jasper is banded by thin contorted beds. These sediments are so

disturbed that little clew as to their structure can be obtained, and so local in extent that no attempt has been made in mapping to differentiate them from the accompanying serpentine.

KNOXVILLE FORMATION (LOWER CRETACEOUS).

Several small areas of sedimentary rock occur which can be definitely assigned on fossil evidence to the Knoxville, or lower Cretaceous. The two most important are north of Mount Lospe, in the Casmalia Hills. The rock is chiefly dark-colored, unaltered argillaceous shale, such as is characteristic of the Knoxville throughout its wide area of distribution in the California Coast Ranges. Sandstone and conglomerate occur in lesser amounts. Brownish-yellow sandstone, similar to that common in the Knoxville in the Coast Ranges several hundred miles farther north, occurs on the border of an irregular area of diabase on Tepusquet Creek, in the San Rafael Mountains, and contains the characteristic Knoxville fossil *Aucella piochii* Gabb (Pl. XIII, figs. 1, 2, 3a, 3b, p. 128). The rock is present only in very small patches, and seems to have been brought up from below by the diabase intrusion. The Knoxville was recognized in one other place in the San Rafael Mountains a few miles north of Zaca Lake, at the base of the series mapped as pre-Monterey, where also it contains *Aucella piochii*. It is very likely that a portion of the areas mapped as pre-Monterey belongs to the lower Cretaceous, but it is not probable that the whole does.

PRE-MONTEREY ROCKS.

Two large areas of sedimentary rocks whose age has not been determined otherwise than that they are older than the Monterey occur in the San Rafael Mountains. They are mapped as pre-Monterey rocks. It is probable that strata of Knoxville (lower Cretaceous) age occur at the base of the series in those areas and that the higher portions represent either the upper Cretaceous or the Eocene, or both. Detailed work was left until another time.

The larger of these two areas occupies the northeast corner of the region shown on the map, and is about 60 square miles in extent. The other lies on the northeastern slope of the high ridge north of Zaca Lake. In these areas are exposed a great series of thin-bedded, dark-colored, locally greenish shale alternating with more massively bedded sandstone, which is in places of a very granitic nature. Conglomerate, much of it plainly evidencing its origin from granite, occurs in minor horizons. Knoxville fossils were found in a gritty greenish sandstone near the lowest portion of this pre-Monterey terrane, about 2 miles north of Zaca Lake. The higher portion seems to be the continuation of a formation in San Luis Obispo County that

has been considered upper Cretaceous and of one in southeastern Santa Barbara County that has been ascribed to the Eocene. Its age is therefore much in doubt. It may also include at the top part of the Vaqueros (lower Miocene), which overlies this doubtful terrane and of which the base has not been definitely determined.

Structurally the strata included in this pre-Monterey group lie beneath the Monterey and upper Vaqueros, but though far older they do not bear so strongly the marks of intense folding as do the brittle Monterey shales. They are, however, steeply upturned, and the lines of folding, as in the case of the other formations, are in general in a northwest-southeast direction.

TEJON, SESPE, AND VAQUEROS FORMATIONS, UNDIFFERENTIATED (EOCENE-MIOCENE).

GENERAL STATEMENT.

The Santa Ynez Range is mostly composed of a thick terrane of marine sediments equivalent to a part or all of the Tejon formation and the Vaqueros formation. The former is Eocene and the latter lower Miocene in age. This terrane comprises a continuous succession of marine sediments of detrital origin, seeming to present no point at which an angular unconformity exists, although the line at the base of the coarse conglomerate containing the Vaqueros fossils doubtless marks a long time interval.

In the preliminary report on the Santa Maria district[a] mention is made of the Sespe formation as being represented here, and a small area of it is shown on the map accompanying that report. The Sespe formation belongs to the Eocene or Oligocene and is a distinct formation above the Tejon and below the Vaqueros. It occurs extensively in the Santa Ynez Mountains north of Santa Barbara, and an outcrop of blood-red sandstone in this range 3½ miles south of the Santa Ynez Mission was indicated on the outline map as belonging to the Sespe because of its lithologic resemblance to the typical rocks of this formation. This small area has, however, not been separately shown on the present map, as there is no good proof of its age. It is quite possible that the Sespe formation is represented in parts of this western portion of the range by rocks not recognizable on the lithologic grounds which are deemed sufficient for the determination of this formation in the vicinity of Santa Barbara or the Ojai Valley, to the east; or it may be that sedimentation was not operative in the western part of the range during Sespe time, and therefore that rocks of that age are lacking from the geologic section in this region. The amount of work done in the Santa Ynez Range does not warrant a full discussion of the structure and relations of

[a] Bull. U. S. Geol. Survey No. 317, 1907, pp. 1-69.

its rocks stratigraphically below the base of the Monterey (middle Miocene) shale.

Strata corresponding to the upper portion of the Tejon-Sespe-Vaqueros terrane have been recognized also in the San Rafael Mountains, where they are exposed at the base of the Monterey (middle Miocene), and it may be that the pre-Monterey rocks are in part equivalent to the lower portion of this terrane. The Vaqueros and possibly part of the Tejon are present also in the Casmalia Hills.

LITHOLOGIC CHARACTER.

The lower portion of the terrane is made up of a thick series of greenish-gray coarse and fine sandstones, many of them concretionary in character, interbedded with dark, fine-grained, thin-bedded shales in lesser amount. Toward the middle of the terrane the shale increases in amount, alternating with thin beds of sandstone. Much of the shale has a characteristic olive-gray color, and owing to its hard, gritty, brittle nature it makes excellent road material for the Santa Ynez Valley. The shales and sandstones give place above the middle of the terrane to deposits of shallow-water character—coarse sandstone and a great quantity of coarse, in many places greenish or reddish, gravelly conglomerate. This conglomerate contains abundant Vaqueros fossils and probably represents the base of that formation and a period of shallow-water conditions with which the Vaqueros began. The conglomerate gives place in turn to more shale and sandstone, which continue to the summit of the terrane. At the top there is a conformable gradation into the Monterey (middle Miocene) beds, the summit of the Vaqueros being marked by a calcareous zone in many places—as, for instance, southwest of Lompoc, where the two formations are divided by a very prominent exposure of hard limestone. This limestone is quarried and used in the refining of beet sugar. Sandstone, shale, and conglomerate belonging to the Tejon-Sespe-Vaqueros terrane occur at the seaward end of the Casmalia Hills. They form a series conformably underlying the Monterey (middle Miocene); but they are separated from beds of flint and shale that can be definitely assigned to the latter formation by an intervening horizon many hundred feet thick of soft, light-brown, clayey, alkaline shale that is almost invariably full of crystalline gypsum. Here the conditions existing during the period of transition from typical Vaqueros to typical Monterey sedimentation must have been very different from those prevalent over the areas occupied by the Santa Ynez and San Rafael ranges. Acidic volcanic ash is interbedded with the Tejon-Sespe-Vaqueros strata in the Casmalia Hills. The occurrence of the ash and the alkaline

shale is mentioned by H. W. Fairbanks in the two quotations given under the heading "Previous knowledge of the geology," pages 12–13, and this author discusses them further in his paper there cited.

STRUCTURE AND THICKNESS.

Like all the Tertiary and pre-Tertiary formations of this region the deposits under discussion have been subjected to folding that has left none of them in an undisturbed attitude. But as they consist in large part of soft sandstone and conglomerate with interbedded layers of sandstone and clayey shale, they have not been so violently fractured and disturbed as much of the brittle shale of the lower portion of the Monterey (middle Miocene). The high ridge of the Santa Ynez Mountains from Point Conception eastward is formed by a great monocline in the sandstone of this terrane, dipping toward the sea on the south at an angle of about 30°. North of this ridge occurs a longitudinal depression in the range in which the folds of the beds are rather low; and still farther north, bordering the Santa Ynez Valley, these rocks are considerably disturbed, dipping in various directions and at all angles between 15° and the vertical. The general inclination of the beds on the north side, however, is northward, the structure of this part of the range, broadly viewed, being anticlinal. In the San Rafael Mountains the Vaqueros strata are steeply folded along northwest-southeast lines, in conformity with the overlying Monterey. A marked example of the way in which the soft, coarse conglomerate has been left little affected occurs in Buckhorn Canyon, where thick beds of this rock, probably the basal part of the Vaqueros, lie almost horizontal.

The Tejon-Sespe-Vaqueros rocks have a thickness of at least 5,000 feet in the Santa Ynez Mountains, and further work will probably allow these figures to be considerably increased.

AGE AND FOSSILS.

At least two distinct faunas are found in the Tejon-Sespe-Vaqueros strata. The lower is characteristically Eocene, and similar to that of the Tejon formation of the type locality; the upper contains many of the species found at the type locality of the Vaqueros formation, which is the standard lower Miocene of the central California province. So far as is definitely known no species bridges the gap between these two faunas, either here or elsewhere in California, although the beds containing the two are apparently conformable not only in the Santa Ynez Range but also locally as far north as Martinez, east of San Francisco Bay.

The following tables show the fossiliferous Tejon and Vaqueros localities and the species of fossils found at each. (See map, Pl. I, in pocket; and illustrations of fossils, Pls. XII to XXVI, pp. 126–154.)

Tejon (Eocene) fossils from the Santa Maria district, California.

	4507.	4509.	4513.	4518.
Cardium brewerii Gabb (Pl. XII, fig. 1)	×			×
Codakia? sp. a	×			
Conus cf. hornii Gabb				×
Crassatellites collina Conrad (Pl. XII, figs. 2a, 2b, 3)	×	×		×
Dosinia elevata Gabb	×			
Fusus occidentalis Gabb	×		×	×
Ficus mamillatus Gabb (Pl. XII, figs. 5a, 5b)	×			×
Glycymeris cf. veatchii Gabb var. major Stanton	×	×		×
Mactra cf. uvasana Conrad			×	
Meretrix uvasana Conrad	×			
Meretrix sp.			×	
Neverita? sp.			×	
Nucula truncata Gabb				×
Ostrea idriaensis Gabb (Pl. XIV, figs. 1a, 1b)	×			×
Pecten (Chlamys) yneziana Arnold (Pl. XII, fig. 4; Pl. XIII, figs. 6a, 6b)	×	×		×
Phacoides cumulata Gabb (Pl. XIV, fig. 2)				×
Phacoides (Miltha?) sp.	×			
Tellina? sp.		×		
Turritella (martinezensis Gabb var.?) lompocensis Arnold (Pl. XIII, figs. 5a, 5b, 8)		×		
Turritella uvasana Conrad (Pl. XII, fig. 6; Pl. XIII, fig. 7)	×	×		×
Venericardia planicosta Lamarck (Pl. XIII, fig. 4)	×			×

4507. Just above San Julian ranch house, 1 mile southeast of bench mark 603.
4509. Sharp turn in road in San Miguelito Canyon, 4½ miles S. 20° W. of Lompoc bench mark 95.
4513. South side of El Jaro Creek road, one-half mile west of bench mark 927.
4518. Three miles north of Sudden, on north flank of 1,912-foot hill.

Vaqueros (lower Miocene) fossils from the Santa Maria district, California.

	4478.	4504.	4508.	4510.	4511.	4512.	4514.	4516.	4517.	4519.	4520.	4521.
Balanus cf. estrellanus Conrad									×		×	
Cardium aff. quadrigenarium Conrad		×							×			
Chione cf. mathewsonii Gabb						×						
Conus sp.							×					
Crassatellites (?) sp.					×							
Gasteropod, genus and species indet.								×				
Meretrix (?) sp.								×				
Modiolus yneziana Arnold (Pl. XV, fig. 2)		×										
Mytilus cf. mathewsonii Gabb											×	×
Ostrea eldridgei Arnold (Pl. XVI, fig. 2; Pl. XVIII, figs. 6a, 6b)	×	×		×			×					×
Ostrea, new species, near titan Conrad		×							×			×
Pecten vanvlecki Arnold (Pl. XVII, figs. 1, 2)	×											
Pecten (Lyropecten) bowersi Arnold (Pl. XVIII, fig. 5)												×
Pecten crassicardo Conrad (Pl. XVIII, fig. 1)												×
Pecten lompocensis Arnold (Pl. XVIII, figs. 2, 3, 4)												×
Pecten magnolia Conrad (Pl. XVI, fig. 1)	×	×	×		×	×			×	×	×	
Pecten sespeensis var. hydei Arnold (Pl. XVII, fig. 3)	×											
Solen sp.								×				

Vaqueros (lower Miocene) fossils from the Santa Maria district, California—Continued.

	4478.	4504.	4508.	4510.	4511.	4512.	4514.	4516.	4517.	4519.	4520.	4521.
Terebratalia kennedyi Dall (Pl. XVII, fig. 4a, 4b, 4c, 4d)												×
Purpura vaquerosensis Arnold (Pl. XV, figs. 1a, 1b)		×										
Turritella sp. indet			×									
Turritella ineziana Conrad (Pl. XVI, fig. 3)							×	×	×			
Turritella variata Conrad (young?)								×				

4478. Two miles south of Santa Ynez, on knoll just east of mouth of Ballard Canyon.
4504. Three-fourths of a mile up ridge northeast of San Julian ranch house, 1¼ miles east of bench mark 603.
4508. El Jaro Creek, one-fourth mile east of Salsipuedes Creek, southeast of Lompoc.
4510. Five miles north of Concepcion, one-fourth mile west of mouth of Escondido Creek.
4511. Float on hillside along east side of Los Amoles Creek, 1 mile above El Jaro Creek.
4512. Ridge between Los Amoles and Salsipuedes creeks, 10½ miles S. 33° E. of Lompoc bench mark 95.
4514. About 10 miles west of Santa Ynez, on south bend of river 1½ miles southeast of bench mark 552.
4516. South of Santa Ynez Mission, 2½ miles up Alisal Creek, at mouth of valley on east.
4517. Three miles north of Sudden, on north flank of 1,912-foot hill, above locality 4518, which is Eocene. (See p. 29.)
4519. On ridge 2 miles east-southeast of El Jaro Creek, bench mark 603, one-half mile west of 1,111-foot hill.
4520. West side of ridge between Los Amoles and El Jaro creeks, 1 mile west of bench mark 603.
4521. Lime quarry 5 miles southwest of Lompoc.

MONTEREY SHALE (MIDDLE MIOCENE).

GENERAL STATEMENT.

A great series of fine shales, largely of organic origin, overlies conformably the coarse and fine sedimentary deposits of the Vaqueros. These shales make up the Monterey formation and are probably representative of the whole of middle Miocene time. The series is of great thickness and is doubly important as the probable source and the present reservoir of the oil. The areal extent of the Monterey is not adequately represented on the map. It doubtless covers as one continuous sheet the whole basin between the Santa Ynez and San Rafael mountains, as well as a large part of these ranges, but it is concealed over considerable areas by later deposits, which are in many places very thin. The character, structure, and relations of the Monterey have been the chief subject of the present study.

The name Monterey was given by William P. Blake[a] in the early fifties to an organic shale formation typically developed near Monterey, in central California. It is very extensive in the California Coast Ranges, being the "bituminous shale" described by Whitney[b] as occurring at widely separated points north and south of the Golden Gate. Its age is generally taken as middle Miocene. It is the source of much of the petroleum found in California. The shale characteristic of this unique formation is not similar to ordinary clay shale, but is composed largely of the remains of minute marine organisms. In an

[a] Proc. Acad. Nat. Sci. Philadelphia, vol. 7, 1855, pp. 328-331.
[b] Geological Survey of California, Geology, vol. 1, 1865, p. 137.

unaltered condition it resembles chalk, but is of siliceous instead of calcareous composition.

The Monterey in the part of California treated here may be divided on lithologic grounds into two parts, although there seems to be perfect conformity throughout the series. There is no definite dividing line to be drawn, but taken as a whole the lower half, composed chiefly of hard, metamorphosed, in places flinty shales, is distinct from the upper half, in which soft shale, giving evidence to the naked eye of its organic origin, is predominant.

LOWER DIVISION.

The fossiliferous limestone at the top of the Vaqueros is overlain conformably by hard calcareous and flinty unfossiliferous shale characteristic of the base of the Monterey. In places the limestone at the top of the Vaqueros is not well developed, but is replaced by a series of thin-bedded, in the main fairly hard, siliceous, calcareous, and somewhat argillaceous shales of coarse and fine texture, in which no well-defined line of demarcation between the two formations is to be drawn. The Vaqueros and Monterey terranes taken as wholes are distinct units, representing periods of deposition of entirely different character. As indicated by the rocks, deposition was continuous between the Vaqueros and Monterey and the change in character came suddenly, although less so in some places than in others. The general nature of the Vaqueros series is detrital; that of the Monterey is organic. The former contains many well-preserved molluscan forms, the latter few. Close to the line between the two, beds predominatingly of a gravelly or sandy nature or those bearing fossil mollusks are considered part of the Vaqueros; those of a fine texture and of flinty or opaline or chalcedonic nature, part of the Monterey.

Above the transitional limestone horizon between the Vaqueros and Monterey the lower half of the latter formation consists of a thick series of thin-bedded, hard, brittle, siliceous and calcareous shales, with local gradations on the one hand into beds of the hardest flint and on the other into soft diatomaceous earth. Near the base there is usually a horizon of black, brownish, or wax-colored flint in heavy beds one to several feet thick, and similar massive beds of peculiar sand-colored limestone with characteristic lamellar weathering. The greater part of the series is made up of brittle siliceous shale, usually much fractured and rather commonly crumpled, in beds averaging about one-half to 1 inch in thickness, in places alternating with thin shaly calcareous beds or massive strata of limestone. Pls. III, *B*, and VI, *B* (p. 46), show outcrops of typical flinty shale of the lower division. Beds of flinty shale or of pure flint are included here and there. The flint is of different colors—amber, black, milky, red, brown, etc.—and of different degrees of translucency. Much of it has been fractured and recemented with chalcedonic veins.

A. CHARACTERISTIC EXPOSURE OF VOLCANIC ASH NEAR BASE OF MONTEREY FORMATION.

At point where Cuyama River enters the Santa Maria Valley. Photograph by Ralph Arnold.

B. UPTURNED AND CONTORTED SEMIFLINTY MONTEREY SHALE.

On Sisquoc River, 5 miles east of Sisquoc. Heavy oil is exuding at a point immediately to the right of the man. Photograph by Ralph Arnold.

It is in some localities banded with fine white laminæ or with bands more translucent than the rest. These bands run parallel with the bedding, and commonly show intricate contortions. The flint fractures conchoidally. From the flint there is every step in the gradation through rocks of less hardness and flinty, compact character to soft white diatomaceous shale. The soft unaltered shale in which the constituent diatom tests are plainly to be seen occurs sparingly, however, in the lower division. A striking example of its occurrence at that horizon can be found at the very base of the Monterey on the San Julian ranch, at the junction of El Jaro and Salsipuedes creeks, where it is pure, soft diatomaceous earth in thick beds, associated with flint and lime and overlying the hard fossiliferous, calcareous conglomerate of the Vaqueros. The specimen of analysis 3 (p. 45) is from this point. The varieties of shale are very numerous, but there is no departure from the general siliceous and calcareous types so peculiar to this formation. There is no common clay shale or slate derived from it, and only very locally is there an appearance of a sandy texture. In the San Rafael Mountains the series has a somewhat different character, especially at the base, where a considerable amount of sandstone, in some places soft and in others quartzitic, is interbedded with the hard calcareous shales. Hard, coarse, yellow and grayish volcanic tuff of acidic nature is interbedded with the Monterey in the vicinity of Cuyama River (see Pl. III, *A*), and elsewhere the lowest portion of the formation is marked by beds of tuff of local extent. At the east end of the Santa Rita Hills the Vaqueros grades into the Monterey through beds of coarse basic tuff composed of small fragments of glass and crystals of various kinds and of large fragments of pumice. Round bowlders or nodules of very fine grained basalt that look like volcanic bombs are included in this tuff.

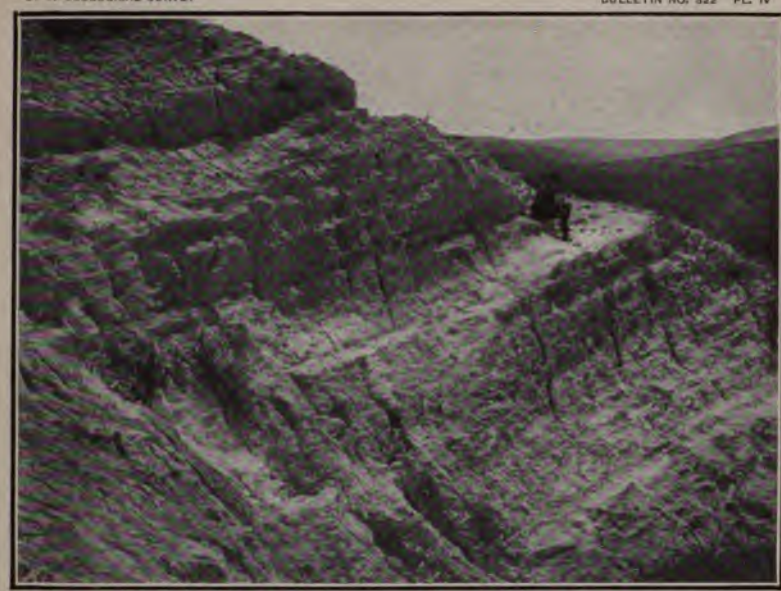
The series of hard shales of the lower division is commonly impregnated with bituminous material. The limy beds have almost universally a bituminous odor and some of them contain pockets of tarry oil. The same is true of the flint with the difference, however, that the limestone is impregnated with petroleum, owing to its porosity, whereas the oil in the compact flint seems more commonly to be contained along lines of fracture or in cavities. The great mass of the hard, brittle shales has in general a similar odor or is discolored with oil. This hard shale series, especially the lower portion of it, and in places possibly the uppermost sandstone of the formation just below it, contains the principal oil-bearing zones in the developed fields. The fact that this shale is so brittle and fractures when folded has an important bearing on the storing of oil in this portion of the Monterey. The fracturing produces cavities in which the oil can collect while the softer unfractured shales adjacent remain more or less impervious to the oil.

UPPER DIVISION.

The line of division between the lower and upper portions of the Monterey is rather arbitrary, yet if each portion is taken as a whole the lithologic distinction is marked, and the separation is made natural by the areal limitations of the outcrops of one or the other in various places. Where they are in contact a conformity between the two halves of the formation is evident and a gradation occurs from the porcelaneous and flinty shales of the lower part into the light-colored, earthy beds of the upper. Such is the occurrence, for instance, near the north edge of the hills 4 miles west-southwest of the town of Lompoc.

The greater part of the upper division is made up of white or light chocolate-colored diatomaceous shale, usually of light weight and porous, but grading in places into heavier and harder, more compact, brittle, porcelain-like shale. The soft shale is extremely fine grained, rarely being at all gritty. The bedding is characteristically very thin, but where great masses of the soft white shale, which goes by the name of diatomaceous earth, occur, lines of bedding are usually indistinguishable, except here and there on thin projecting laminæ produced by weathering, or on the upper surface of small cavities due to the eating out of less resistant patches. Pl. IV illustrates two characteristic types of the soft unaltered shale. In the upper view it is massive, and bedding planes are almost indistinguishable except for lines brought into relief by weathering and erosion. In the lower view it is slightly more compact and lies in distinct platy layers. Major bedding planes from a fraction of an inch to several inches apart are distinctly apparent, and there is a further laminated structure that enables the shale to be split into plates of extreme thinness. An artificial cut through somewhat disintegrated shale of the upper part of the Monterey is shown in Pl. VIII, *A* (p. 78). The typical unaltered diatomaceous shale is pictured in Pl. V, *A*. The small round diatom tests of which it is largely composed are faintly distinguishable with the naked eye in the photograph. In general, both the softer and harder varieties of the Monterey shale, owing to their siliceous composition, do not give way readily to decomposition or weathering. Local chalcedonic lenses are to be found in this series roughly following the bedding planes in unaltered shale, as well as horizons of hard, porcelaneous, usually much-fractured shale; but the latter does not become predominant over the softer shale as it does in the lower division.

The white chalklike deposits of this formation are not fully described by the use of the word shale in its ordinary sense. Especially in the massive deposits, where bedding is not very apparent, it has neither in composition nor lamination the character of ordinary shale. But this word has come into use in connection with the Monterey for lack of any other. The major portion of the formation, however, does



A

B

SOFT WHITE DIATOMACEOUS SHALE.

A. Characteristic exposure north of Casmalia. *B*. Detail of weathering at Burton Mesa, east of Pine Canyon. Photographs by Ralph Arnold.

A

B

DIATOMACEOUS SHALE.

A. Typical soft, white, unaltered specimen. *B*. Red, brittle, and heavy specimen; metamorphosed by the burning of its hydrocarbons.

resemble shale in its thin stratification, the great difference being in the siliceous instead of argillaceous composition. Locally there are beds of clayey nature in the upper division which form a connecting link between the "chalk rock," as the diatomaceous shale is colloquially termed, and common clay shale. Characteristic oval and lenticular yellow concretions of hard lime are commonly included in the shale of the upper division. They range in diameter from a few inches to 2 feet or more. In many places they occur at irregular intervals and of irregular size along a bedding plane, locally displacing the ordinary shale and interrupting the continuity of not merely one bed but many thin beds. They are invariably elongated parallel with the bedding.

Volcanic ash is interbedded with the soft shale of the upper division in the hills immediately south of Lompoc. It is very fine grained, soft, and uncompacted, and probably corresponds in composition to rhyolite. It somewhat resembles the pulverulent diatomaceous earth, but is easily distinguishable by its grayish color and grittiness.

The upper portion of the Monterey, like the lower, is to a large extent impregnated with bituminous material. It is apt almost anywhere in this region to give out a bituminous odor when broken into or to show a brownish discoloration due to the presence of oil. In places the shale, otherwise white, is specked with minute black spots of bitumen. Thin sandy layers occur sparingly interbedded with the shale, and these almost without exception have absorbed considerable oil and have a dark-brown color and strong odor. But these beds of sand are very rare and make up no appreciable proportion of the series.

The soft varieties of the Monterey shale are almost invariably alkaline and have a salty taste. They contain an abundance of salts easily soluble in water that form characteristic wooly coatings of efflorescence on the surface of outcrops. This is especially true near the summit of the formation, where a soft claylike gypsum-bearing shale locally marks the contact with the Fernando above. This gypsum is crystallized in plates along seams and bedding planes much like the gypsiferous clay of the Casmalia Hills, which is supposed to be Vaqueros in age. Zones of gypsiferous shale occur also at other places in the upper division of the Monterey, but it is not known whether there are any single horizons at which it is constant. Where the gypsum occurs the shale is usually of more argillaceous character and bears a closer resemblance to ordinary clay shales. The significance of this alkalinity in the Monterey is unknown. The organic shale is considered to be of marine origin in fairly deep water, and owing to the almost complete absence of all but the finest grained detritus the alkalinity can not be considered as proof of shallow-water or brackish-water origin. The salts may have some relation to the chemical changes involved in the production of petroleum.

DIATOMACEOUS EARTH DEPOSITS.[a]

The infusorial earth, diatomaceous earth, diatomaceous shale, or tripoli, as the same material is variously called, of which the upper division of the Monterey is chiefly composed, is of fairly pure quality in this region and of considerable economic value, especially as it occurs in inexhaustible quantities close to transportation facilities. The areas of it are extended and the series of strata very thick. Deposits suitable for working occur in the hills immediately south of Lompoc; southwest and west of Lompoc; along the river east of Lompoc; in the northeastern and southeastern portions of Burton Mesa and over the Purisima Hills east of it; over wide areas in the Purisima Hills southwest, south, and southeast of Los Alamos; on the southern flanks of the Santa Rita Hills; 1½ miles north of the Santa Ynez Mission; in smaller amounts near the east edge of the area mapped, a mile north of Santa Ynez River; underlying the San Antonio terrace south of Casmalia; over a wide region southeast, east, and north of Casmalia; on Graciosa Ridge, and in the region extending from the head of Howard Canyon to a point southeast of Sisquoc. The uses to which this material can be put are numerous and the demand for it is increasing.

COMPOSITION OF THE MONTEREY SHALE.

MATERIAL OF SHALE.

The composition of the Monterey shale is of especial interest. One is able to see on examining the soft unaltered variety with a hand lens, or sometimes even with the naked eye, that it is full of small round dots ranging, to speak roughly, from 0.1 mm. to 1 mm. in diameter. These are the skeletons of minute marine organisms called diatoms. They are a low order of plants or algæ having a framework of silica. They are locally so closely packed together that they seem to form the bulk of the deposit. In some of the rock they are so well preserved that the details of their structure can be made out with the aid of higher magnification. But elsewhere they appear crushed and almost unrecognizable. It is a question how much of the shale is formed of the diatom frustules that have been thus crushed. The shale in which the remains are well preserved and abundant is extremely soft and white and may be rubbed at a touch into a powder like flour. The round diatom disks are white and soft just like the matrix surrounding them, which looks as if it, too, were made up of diatom remains that had preserved their form less perfectly. Shale in which the remains are less prominent has

[a] A more extended description of these diatomaceous deposits is published in "Contributions to Economic Geology, 1906" (Bull. U. S. Geol. Survey No. 315, 1907, pp. 438–447), under the title "Diatomaceous deposits of northern Santa Barbara County, Cal."

the same appearance, as if formed of the same materials, but compacting and crushing seem to have gone a little further so as to obscure the organic remains. Almost all the shale of the upper division of the Monterey contains diatom remains where it has not undergone alteration into the hard varieties. The same is true of the soft shale wherever it occurs in the lower portion of the formation, the most notable example being at the very base of the Monterey on the San Julian ranch east of the junction of Salsipuedes and El Jaro creeks, where it is associated with hard flint and limestone immediately overlying the fossiliferous limestone and conglomerate of the Vaqueros. There the shale is earthy, pure white, and full of diatoms.

When the shale has undergone alteration and hardening into the porcelaneous and flinty varieties the constituent organic remains are usually obscured, but here and there even in these the impressions may be found preserved. Usually an examination under the microscope reveals scattering circular and oval areas, of slightly different composition or character from the surrounding rock, that look as if they might represent the forms of organisms. In speaking of the exposure of Monterey rocks between the mouth of Schumann Canyon and Lions Head on the southern flank of the Casmalia Hills, H. W. Fairbanks says:[a] "The basal portion of the series is composed chiefly of clear, flinty rocks, showing abundant remains of organisms visible to the unaided eye." And in speaking of the harder varieties of Monterey shale in general of the Point Sal region he says:[b] "When examined with the hand lens much of the rock is seen to be thickly specked with little round dots, averaging, perhaps, a millimeter in diameter. Under the microscope * * * the circular areas did not appear as numerous as in the hand specimen, and were only faintly distinguished by clearer polarization."

Aside from the diatoms the rocks of the Monterey contain remains of minute Foraminifera, which have calcareous frames, and Radiolaria, which secrete silica to form their tests. The latter are present sparingly. The common siliceous shale contains very little lime and no Foraminifera have been found in it in this district, although they have been reported from the typical Monterey shale elsewhere. R. M. Bagg[c] found 66 species belonging to 17 genera in chocolate-colored, soft, fine-grained shale of the same formation near Asuncion, San Luis Obispo County. J. C. Branner in the introduction to Bagg's paper, describes the shale as follows: "The shale proper also varies; at some places it is flinty, at others it is somewhat sandy, and at still others it is soft and chocolate-colored, and contains an abundance of well-preserved Foraminifera. * * * The bulk of

[a] Geology of Point Sal: Bull. Dept. Geology, Univ. California, vol. 2, No. 1, 1896, p. 9.
[b] Op. cit., p. 10.
[c] Miocene Foraminifera from the Monterey shale, California: Bull. U. S. Geol. Survey No. 268, 1905.

this shale is made of diatom skeletons. * * * Even when the rocks are flinty they often contain good impressions of Foraminifera." Foraminifera occur in the partially calcareous shales of the Santa Maria district, and in places the limestone is full of them. In some specimens they are perfectly preserved and various kinds may be easily seen with the unaided eye. In other places the limestone shows no trace of organisms; but it is the opinion of the writers that they have been present in such places and have lost their shape, and that foraminiferal skeletons account for a large part of all the Monterey limestone and for the calcareous portion of the limy shales. H. W. Fairbanks says in his paper quoted on page — that the limestone of the Point Sal region "appears to be formed almost exclusively of minute organisms."

Specimens representing different varieties of the Monterey shale and flint were sent to F. J. Keeley, of the Philadelphia Academy of Natural Sciences, who very kindly made examinations of them and reported regarding their diatom contents. (See Pls. XIX and XX.) He found diatoms plentiful in the unaltered earthy shale and less common in the more compact shale and in the less pure, either gritty or argillaceous shale. Sponge spicules were common in all the samples, and in those last mentioned they were more abundant than diatoms. No examination was made of the indurated varieties. Mr. Keeley was unable to make more than a hasty examination, but on request he estimated roughly that the purest material contained from 5 to 10 per cent of diatoms and that the soft shale in which fewer could be seen contained possibly 1 per cent. He found a few Radiolaria but no Foraminifera in the pure siliceous shale, diatoms and next to them sponge spicules being by far the predominant organic remains.

C. S. Boyer, of the Philadelphia Academy of Natural Sciences, kindly identified the species of diatoms in two slides prepared by Mr. Keeley from the two purest samples of diatomaceous earth that were sent to him. Mr. Keeley says: "The lists made by Mr. Boyer cover only the species he saw in the slides sent him, and an exhaustive examination of the material, which would require searching over, say, a hundred slides or more, would probably give a long list of species, many of which might not be seen more than once or twice in the course of such an examination." Nevertheless, these lists probably indicate the commonest species. In the slide made from the shale at the base of the Monterey from the locality above referred to at the junction of Salsipuedes and El Jaro creeks Mr. Boyer found the following diatoms:

Coscinodiscus marginatus Ehrenberg.
Coscinodiscus marginatus var. intermedia Rattray.
Coscinodiscus robustus Grev.
Arachnodiscus (fragment).
Diploneis? (fragment).
Melosira sulcata Ehrenberg (rare).

Mr. Boyer says: "The deposit consists almost entirely of *C. marginatus* and *C. robustus* of various sizes and often without rims. It is impossible, in certain cases, to distinguish between these two forms. The variety *intermedia* is between the two and was created by Rattray."

The second slide was made from soft shale of the uppermost portion of the Monterey, from the Pinal property on the east side of Pine Canyon, on the north flank of Graciosa Ridge. The following diatoms were found:

Coscinodiscus oculus iridis Ehrenberg (abundant) (Pl. XI, fig. XIX).
Coscinodiscus marginatus Ehrenberg.
Coscinodiscus marginatus var. intermedia Rattray.
Coscinodiscus robustus Grev. (Pl. XX, fig. 4).
Coscinodiscus radiatus Ehrenberg.
Coscinodiscus obscurus A. S. (Pl. XX, fig. 2).
Coscinodiscus nodulifer Janisch.
Coscinodiscus heteroporus Ehrenberg.
Coscinodiscus subtilis Ehrenberg (Pl. XX, fig. 3).
Actinoptychus undulatus Ehrenberg (rare) (Pl. XX, fig. 1*a*).
Arachnodiscus ehrenbergii var. californica (fragment).
Lithodesmium cornigerum Brun. (Pl. XX, fig. 1*b*).

According to Mr. Boyer this second sample consists chiefly of fragments of *Coscinodiscus oculus iridis* Ehrenberg, which is a larger and more delicate form than the one predominating in the first, and both he and Mr. Keeley comment on the peculiar absence of it there. The difference in the fauna in these different localities is of interest, inasmuch as the deposit represented by the first slide was at the base of the Monterey and that represented by the second near its summit.

Besides the small organisms that have been described as forming a portion of the shale material, and the less abundant organic remains mentioned on pages 42–43, the deposits of Monterey age contain a considerable percentage of fine siliceous and aluminous matter, probably of detrital origin, in the shape of exceedingly minute clastic grains. The chemical analyses of specimens from different localities show a large percentage of alumina, the presence of which is probably the result of fine argillaceous silt settling on the sea bottom to aid in the formation of the shale. The origin of the silica is more in doubt. There is no question of the presence of a large amount of siliceous diatom skeleton material, and the many fine-rounded and angular particles of quartz revealed by the polarizing microscope in the unaltered shale indicate that the sediments derived from shore areas carried quartz grains also, but there is no proof as to which of these sources supplied the bulk of the silica, of which the shale is mostly composed. Besides the recognizable diatom remains it is impossible to tell how much of the shale is composed of similar skeletons that have been crushed beyond any semblance of their original form. Comparatively few forms are perfectly preserved, most of

those observed under the microscope being only fragments, and this makes it probable that others are still more fragmentary and in a state of complete demolition. The likelihood, therefore, is that a greater proportion of the pure shale than 5 to 10 per cent, as roughly estimated by Mr. Keeley on the basis of visible forms, is composed of silica derived from diatoms. Radiolaria, which are scattered through the shale sparingly, have contributed somewhat to the organic silica. Whatever conclusion one should come to would apply to almost all of the soft unaltered shale of the siliceous type in the Monterey of the Santa Maria district, as this type is fairly constant. Locally it is varied by an increased proportion of argillaceous material, causing a greater similarity in appearance to ordinary clay shale, or by the presence of lime; but diatoms are visible in practically all of it and the general conditions of deposition seem to have been the same throughout. The conclusion is reached elsewhere (p. 47) that the same probable origin may be assigned to all the siliceous shales of the Monterey, whether hard or soft—or, in other words, to by far the greater part of the formation.

The list of organic constituents of the shale is by no means exhausted by the small organisms of low order so far mentioned. Another important source of silica lies in the abundant sponge spicules, which are only second in number to the diatoms and which are scattered with remarkable persistency throughout the shale. In the slightly gritty beds of soft shale, which occur sparingly, these spicules even predominate over the diatoms, being possibly the cause of the grittiness. They seem also to be less easily obliterated than the fragile diatom shells and to have been preserved in places where slight alteration of the rock has destroyed the latter. One of the commonest and most characteristic features of both the unmetamorphosed siliceous and the calcareous shales is the presence of scales of fish, showing that fish remains found their way to the ooze at the ocean bottom in greater or less abundance. Locally the bones and nearly complete skeletons are also to be found. Delicate mollusk shells, usually of small size, are gathered thickly in some places in the Monterey shale, and at such points may be considered as constituting an appreciable proportion of the total volume of the deposit. As a rule they are crushed and poorly preserved, a fact that lends weight to the theory that a large part of the diatom frustules also have been destroyed. But mollusks are rare in the formation as a whole. Crab shells and claws are occasionally found, usually not whole but in small pieces, as if they had been subjected to conditions favorable to their destruction before coming to rest. Seaweed impressions are not rare. In addition to organic remains of these kinds, the shales, especially the

less purely siliceous varieties, are usually full of small brown scales, spines, and fragments or impressions of nondescript shape which are of organic origin but which can not be recognized as belonging to any particular forms. Here and there, also, large bones are embedded in the deposits. They seem to be those of whales or other large marine vertebrates.

Taken as a whole, the Monterey shale may well be called an organic formation. The practically complete absence of coarse sediments derived from erosion and the abundance of fossil organisms, especially of siliceous skeletons, make it different both in appearance and composition from any other known formation of comparable thickness. The unaltered siliceous shale most nearly resembles chalk, but it contains only a small proportion of lime. Whether or not the organic remains compose more than half or as much as half of the deposit can not be stated.

MICROSCOPIC APPEARANCE.

Under the polarizing microscope little can be made out regarding the structure of the main mass of the soft shale and compact white shale. The groundmass seems to be made up of amorphous colloidal silica surrounding minute grains which are both crystalline and amorphous, but the character of which can not be recognized. Embedded in this are numerous imperfectly angular or more rarely partially rounded crystal particles, probably of quartz. Many of the latter look as if they were due to secondary development rather than originating as clastic grains.

In the more flinty varieties the rock appears to have undergone partial and local crystallization of the silica throughout its mass. In the flint, in which there are alternating, usually crumpled bands of opaque light-colored flint and clear amber-colored or black flint, the opaque bands are composed mainly of amorphous material like that of the softer shale, but in a much more compact state, and the translucent bands are mainly crystalline aggregates. The opaque bands include crystalline particles and, locally, patches of crystal grains like those of the clear flint, and they are included longitudinally by intermittent bands of the clear flint. Furthermore, they are in many specimens of a patchy appearance, parts being less amorphous than others. The bands of the clear flint are composed chiefly of small grains of crystalline quartz, and these are surrounded by a finer grained aggregate of crystalline and amorphous particles. The quartz grains have neither the rounded outlines of waterworn grains nor angular crystalline outlines, but are branching, and appear more like growths. Angular patches of the amorphous silica, many of them showing signs of

incipient crystallization, are included in the clear bands, giving a brecciated appearance. The bands are parallel with the bedding planes. They are commonly followed and more rarely crossed by veins of quartz crystals.

The limestone is made up of granules of crystalline calcite, or calcite showing the beginnings of crystallization. Included in this extremely fine grained, uniform groundmass are larger but yet very small, irregular grains of crystalline calcite, and in places long spicules of the same. In some specimens the granules are more minute than in others and the included larger grains are fewer. In still others, crystallization has entirely altered portions into patches of large, intergrown crystals, leaving angular, unchanged patches sharply marked off, and thus giving an appearance like that of a breccia. The flinty calcareous shale has a minute granular texture, quartz grains both crystalline and semicrystalline being associated with those of calcite. The rock usually has light and dark bands parallel with the bedding, the light bands containing more quartz and having the calcite granules less close together than the darker bands.

CHEMICAL COMPOSITION.

The subjoined table comprises analyses of different specimens and varieties of Monterey shale from the Santa Maria district, with one (No. 5) here included for comparison, of a sample of white bituminous shale from the type locality of the formation at Monterey, farther north on the California coast.

The first three represent typical examples of the unaltered diatomaceous shale of the Monterey. Nos. 3 and 2, respectively, are analyses of the same samples that were found to be rich in diatoms when examined in slides 1 and 2 by Messrs. Keeley and Boyer, as mentioned on pages 40–41. Nos. 4 and 6 are analyses of samples from the same hand specimen, taken within 1 inch of each other, No. 4 showing the composition of unaltered white shale in which diatoms are visible, and No. 6 of the translucent, brittle, flintlike product of extremely local alteration. The next four indicate gradations in the products of the metamorphism. The last analysis (No. 11) represents limestone typical in lithologic appearance of the limestone of the Monterey.

Analyses of Monterey shale.

	Diatomaceous shale.					Flinty shale.					Limestone.
	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.
SiO_2	65.62	72.50	83.19	80.59	86.89	92.88	86.92	92.37	97.02	98.1	.....
Al_2O_3	.....	11.71	.....	.....	2.32	.....	4.27	2.46	.....	Not det.	.....
Fe_2O_3 (total iron)	.....	2.35	.....	.....	1.28	.....	.....	.....	.....	Not det.	.....
CaO	.....	.32	.....	.....	1.43	.....	1.60	1.70	.....	.....	27.86
MgO	.....	.83	.....	.....	Trace.	.....	Trace.	.....	.....	.....	16.64
Alkalies (Na_2O,K_2O)	.....	1.88	.....	.....	3.58	.....	2.48	.....	.....	.....	.....
Ignition	11.00	9.54	.....	.....	4.89	.....	5.13	2.74+ CO_2	.....	.....	.....
	.....	99.13	.....	.....	100.39	.....	100.40	99.27	.....	.....	.....

1. Soft, white diatomaceous shale; Purisima Hills, 3½ miles southwest of Harris, Santa Barbara County, Cal. Analyst, W. T. Schaller, 1907.
2. Soft, white diatomaceous shale; Graciosa Ridge, 3 miles southeast of Orcutt, Santa Barbara County, Cal. Analyst, W. T. Schaller, 1907. Approximate analysis.
3. Soft, white diatomaceous shale; San Julian ranch, at junction of El Jaro and Salsipuedes creeks, Santa Barbara County, Cal. Analyst, E. C. Sullivan, 1907.
4. Soft, white diatomaceous shale; San Antonio terrace, 2 miles south of Casmalia, Santa Barbara County, Cal. Analyst, E. C. Sullivan, 1907.
5. White shale; Monterey, Monterey County, Cal. Lawson, A. C., and Posada, J. de la C., Bull. Dept. Geology, Univ. California, vol. 1, 1893, p. 25. Specific gravity, 1.8–2.1.
6. Gray, glassy porcelain shale; from same hand specimen as No. 4. Analyst, E. C. Sullivan, 1907.
7. White porcelain shale; region of Point Sal, Santa Barbara County, Cal. Analyst, H. W. Fairbanks, Bull. Dept. Geology, Univ. California, vol. 2, No. 1, 1896, p. 12.
8. Opaque flint; Point Sal, Santa Barbara County, Cal. Analyst, H. W. Fairbanks, loc. cit.
9. Hard, black, clear flint; 1½ miles west of Zaca, Santa Barbara County, Cal. Analyst, E. C. Sullivan, 1907.
10. Hard, black, clear flint; Point Sal, Santa Barbara County, Cal. Analyst, H. W. Fairbanks, loc. cit.
11. Bituminous limestone; Redrock Mountain, northeast of Lompoc, Santa Barbara County, Cal. Analyst, George Steiger, 1907.

ALTERATION.

The differences in character and composition between the soft and hard varieties of the Monterey shale have been brought out in the foregoing discussion. The question arises, To what are these differences due? It is difficult to give a decisive answer. The main differences in the gradations from the soft to the hard shales lie in the siliceousness, compactness, hardness, and degree of crystallization. Taken as a whole the lower division is made up largely of hard shale and the upper of soft shale, but gradations from one variety to another within an extremely small space occur in both divisions. In some places a thick series of beds of similar character is marked off from a series of different character. Elsewhere a variation occurs bed by bed, or, in still other places, a single bed or lens of shale of one variety is included within another kind. The softer varieties contain at many points small lenses of hard, brittle, or semiflinty shale elongated parallel with the bedding, or strata in which lenses are strung along at irregular intervals, or single small beds composed entirely of harder material. In such occurrences there seems to be a gradation from one variety to the other, and the outlines of the hard layers are not regular or very definite. For example, the diatom-bearing shale of chemical analysis No. 4 and the glassy

opaline rock of analysis No. 6 were samples taken from the same hand specimen within 1 inch of each other. The mass of the deposit from which the specimen came was soft white shale belonging high in the formation and contained a rough layer, a few inches thick, of the harder material between two beds of the soft rock.

The soft shale has been described in the preceding pages as "unaltered," and in referring to the harder varieties different degrees of "alteration" have been mentioned, for the reason that the best explanation of the origin of the harder rocks appears to be that they are products of metamorphism of the soft variety. It is believed that the soft white and chocolate-colored organic shale represents the original state of the beds of the whole formation, and that a process of silicification and crystallization has caused the changes, this process having been aided possibly by structural disturbances and pressure. The beds of soft shale are usually found in attitudes only gently disturbed, whereas the harder shale is most commonly much folded and is invariably the component rock of folds where the forces have been especially intense. This fact may throw light on the problem of the alteration of the shale, and yet it may be simply the outcome of the removal of the softer portion of the formation in the regions of greatest uplift and disturbance. The chief agent in causing the change was probably infiltrating water carrying silica in solution. In some places the process may have been simply or largely infiltration in the extremely porous original shale and deposition of silica in the interspaces, thus giving rise to hardened and compacted irregular granular aggregates of the original amorphous silica and the new crystalline silica combined, the result being an increase in the total percentage of silica. In more extreme cases the original material was probably partly taken in solution and redeposited, being replaced almost entirely along bands or in spots, and the change being carried to a less extent along other layers and in other areas, or else the replacement was almost complete throughout. As the rock was rendered more compact in this process a shrinkage may have been the result, or the same volume may have been retained and the pores filled. That solution took place along with deposition seems to be shown by the almost complete destruction of the forms of organisms.

It is possible that the differences in the shales may be original, the result of variation in the material deposited. Whole series of beds of different material might have been deposited, giving rise to harder, more siliceous rocks than the soft varieties, and the same material might have been locally deposited in thin beds or in lenses and nodules, or have been intermingled with the others to form the intermediate varieties. But it would be difficult to say what this mate-

A. CHARACTERISTIC EXPOSURE OF FERNANDO GRAVEL.

Second ridge east of Figueroa Creek, 7 miles northeast of Los Olivos. Photograph by Ralph Arnold.

B. SHARP DOUBLE FOLD IN MONTEREY SHALE.

Looking east from point northwest of Zaca Lake; Zaca Peak in distance. Photograph by Ralph Arnold.

rial might have been, and the more or less completely crystalline character of the harder shales shows that metamorphism has taken place. The most plausible theory, therefore, is that the Monterey shale as originally laid down was fairly constant in character and that it has undergone alteration extensively, as well as very locally, through the agency of siliceous waters, the older portions of the formation, and possibly the more disturbed portions, having been most generally subjected to the change. The limestone has in places been altered after a fashion somewhat similar to that of the siliceous shales, being changed to marble, probably as the result of solution and redeposition.

The Monterey rocks likewise show the result of contact metamorphism to a very local extent in the vicinity of the diabase intrusions. The process seems to have been largely one of consolidation through baking. A limestone specimen obtained near the diabase intrusion north of Zaca Peak, in the San Rafael Mountains, gives an excellent illustration of shearing. The calcite crystals have all been arranged parallel and greatly elongated, so as to give the rock a schistose structure.

STRUCTURE AND THICKNESS.

The Monterey has nowhere been left undisturbed. In places it has been but gently folded. Pls. IV (p. 36), VIII, *B* (p. 78), and IX (p. 80) show examples of moderate tilting. But at other places, as at that pictured in Pl. VI, *B* (p. 46), it has been thrown into folds so sharp and closely spaced that the succession of the beds and thickness of the series are difficult to make out. The details of its structure are discussed under the heading "Structure" (pp. 76–78). The thickness of the whole series is at least 5,200 feet. Each of the two divisions comprises a maximum known thickness of 2,600 feet. No single complete section of the whole could be obtained.

EVIDENCE OF AGE.

A paucity of recognizable molluscan fossils is one of the prominent characteristics of the Monterey in this region, as in most others in the Coast Ranges where it outcrops. Moreover, the other fossils that it contains are of little value in indicating its age. Its position in the geologic column is determined by the lower Miocene fossils found just below its base in the Vaqueros and by the upper Miocene fossils found at or near the base of the Fernando formation, which lies unconformably above it.

The following two species of mollusks occur in the Monterey diatomaceous shale on the road just above the Pinal Oil Company's office, southeast of Orcutt: *Arca* aff. *trilineata* Conrad, *Phacoides* aff. *acutilineatus* Conrad.

METAMORPHISM OF THE SHALE BY COMBUSTION.

At many different places in the Santa Maria district and elsewhere the oil-bearing shale has been burnt to a pink or deep brick-red color, or turned into a hard vesicular rock like scoriaceous lava, as shown in Pl. V, *B*, p. 36. This metamorphism is due to the combustion of the hydrocarbon content. Though the combustion is usually local in its effects, the number and wide distribution of the occurrences of burnt shale lend importance to the phenomenon. Such altered shale is of some value as indicating where the rock has been bituminous and where the conditions have favored the occurrence of seepages.

LOCALITIES WHERE THE SHALE IS AT PRESENT BURNING.

A number of localities have been observed at which combustion is at present or has been in recent years in progress within the Monterey shale. One of these is on the north side of Graciosa Ridge, south of the Santa Maria Valley, near the Rice ranch oil well No. 1. When this locality was visited by the writers early in the autumn of 1906, a fire was burning underground in the shale, causing a smoke of disagreeable odor to issue from the surface and making the ground hot over an area of many square yards. Oil was oozing up at various points near by, and the ground was heated in the neighborhood of all these seepages. The holes from which vapor issued were coated with delicate crystals of sulphur. At the point where the burning was actually going on and all about in the vicinity, for a distance of several hundred feet in some directions, the shale was altered to a bright-red color, or baked almost to the hardness of compact igneous rock, or rendered vesicular like lava.

There can be no doubt that this fire was supported by the bituminous material in the shale, and it was probably started by brush fires, though these had occurred a good many months before, as shown by the new growth of the bushes. It was said that there was a brush fire about January 1, 1906, which started the fire in the shale, and that futile attempts to put it out by dumping dirt to smother it had been made ever since that time. It seems likely, however, that this same fire has been in progress for several years. This likelihood is borne out by other accounts. It is stated that sometimes during the course of brush fires on the hills sudden darts of flames may be seen at night from a considerable distance—the result of the setting on fire of gas escaping from the rocks.

Other cases of burning in the shale have been observed in recent years at the San Marcos ranch in the Santa Ynez Valley, and at the mouth of Rincon Creek, on the coast near Santa Barbara, as described by H. C. Ford.[a] The phenomena exhibited resemble those

[a] Bull. Santa Barbara Soc. Nat. Hist., vol. 1, No. 2, October, 1890.

of solfataras and have given rise to the opinion that volcanic activity is present in this region. This so-called "Rincon volcano" existed before 1855, being referred to in the Pacific Railroad reports; this shows that the burning has continued a long time.

TYPICAL OCCURRENCES OF BURNT SHALE.

Outcrops of burnt shale occur in eight or ten localities in the Santa Maria district. The best examples are at various places along the ridge of the Casmalia Hills from a point south of Schumann to Waldorf; on the north and south sides of Graciosa Ridge; and on Redrock Mountain 4 miles southeast of Los Alamos. In each of these regions every stage of alteration is exhibited, from the slightly discolored shale to hard slaglike rocks of varying shades of red and black. The area of altered shale in the different localities ranges from about a hundred square feet to a half a square mile or more, as at Redrock Mountain. In each the burnt rock is surrounded by unaltered, usually soft, white, diatomaceous shales which in most places show the planes of stratification. At no point observed was a sign of stratification left in the baked shale. In every occurrence the shales in the neighborhood are bituminous and asphalt deposits are usually adjacent.

The largest area of altered shale is on the summit and surrounding ridges of Redrock Mountain. This is the highest of the hills in the basin region between the San Rafael and Santa Ynez mountains, being 1,968 feet above the sea; the height of most of the summits in the vicinity is from 1,000 to 1,500 feet. Redrock Mountain seems to owe its prominence, at least in part, to the metamorphosed shale that forms its summit. Likewise, in the 800-foot hill on the southeast side of Schumann Pass, the capping of this same character, resembling volcanic rock, seems to have caused the topographic relief. The metamorphism in these localities probably took place a long time ago. At Redrock Mountain great deposits of asphalt are in places in contact with the altered shale, and there is a large area of shale impregnated with bitumen.

DEPTH TO WHICH ALTERATION HAS EXTENDED.

The depth to which alteration has extended below the surface in these occurrences is difficult to determine. A cliff of burnt shale 50 to 100 feet high is exposed 4½ miles due south of Guadalupe, and the difference of elevation of points in the Redrock Mountain neighborhood where the altered rock outcrops amounts to several hundred feet. That such metamorphism of the shale has not been solely a surface phenomenon is shown by the fact that burnt shale has been found at considerable depths in drilling. Mr. Orcutt, of the Union Oil Company, exhibited samples of red shale, coming from depths of 950

to 1,040 feet below the surface in Hill well No. 1, in the Lompoc field, which are identical in appearance and texture with the burnt shale elsewhere. Traces of petroleum were associated with the upper stratum of burnt shale in this well. In numerous other wells in the Santa Maria field red shale, doubtless burnt, was found at depths ranging between 90 and 330 feet below the surface. The hardening consequent on the burning has in some places rendered the rock difficult to pierce with the drill.

LITHOLOGIC CHARACTER OF BURNT SHALE.

The burnt shale exhibits all stages of change from a slight induration and discoloration, due, probably, to oxidation of iron, to an extreme hardening and partial fusion. Where slightly altered, the normal white shale assumes a light-pink color. From this stage it passes through various shades of rose and brick-red and deepens in color to a reddish, bluish, or greenish black, or even a true black. In the advanced stages of change it becomes a rough, brittle, reddish, porous slag, like vesicular lava, or a very hard, compact, dark, and dull-colored rock, looking something like a compact igneous rock. An example of partly vesicular and partly compact burnt shale is shown in Pl. V, *B* (p. 36). Burnt shale is not crystalline, but the texture is so variable as to give a patchy appearance to surfaces. In one place it may be compact and black, nearly full of irregular cavities, surrounded by patches of different colors; in another, vesicular and reddish. Whereas the weight of the original shale is slight, the lighter varieties having a specific gravity less than that of water, the excessively burnt shale is very heavy. The material has evidently contracted to much less than its original volume, the angular cavities and irregular vesicles being one consequence of this contraction.

Under the microscope the rock in the more advanced stages of alteration appears to have an exceedingly fine grained, amorphous, porous groundmass, discolored with reddish-brown or gray stains. Black filaments and dots appearing like carbonaceous material are common. Exceedingly minute rounded and irregular grains scattered through the whole, but forming no appreciable proportion of it, are the only portions visible under crossed nicols. They extinguish four times in a revolution of the field and are probably clastic quartz grains. These are characteristic of the unaltered shale as well.

G. H. Eldridge[a] notes an occurrence of burnt shale near the old Blake asphalt mine, south of Graciosa Ridge. He says: "The shale now appears red, ashlike to hard and clinker-like, glazed, or silicified; bodies of bitumen contained within this have the appearance of a coke, as though derived from the solid fixed carbon of the petroleum."

[a] The asphalt and bituminous rock deposits of the United States: Twenty-second Ann. Rept. U. S. Geol. Survey, pt. 1, 1901, p. 428.

The likeness of varieties of the burnt shale to volcanic rocks is indicated by the fact that Thomas Antisell, in his account of the geology of the Coast Ranges in the Pacific Railroad reports,[a] describes "scoriaceous" and "amygdaloidal lava," "whitish-gray, hard trachytic rock," "volcanic," and "igneous rocks" in the region of Santa Ynez River, evidently having reference to the burnt shale. He considered these rocks to be eruptive masses, forming the oldest and axial rocks of the hill ranges, whereas they are part of the Monterey shale, which overlies the basement formation. He regarded the associated diatomaceous shales in some places, although not in others, as "magnesian" and "tremolite" rocks of igneous origin, and refers to the places where the shale is burning as examples of present volcanic activity.

CAUSE OF THE ALTERATION.

There can be little doubt that the burnt condition of the shale is in all places the result of heat produced by combustion of its hydrocarbon content. The phenomenon is confined to the Monterey shale, which is the source of a large part of the California petroleum, and to those regions in which this formation is extremely bituminous. The shale in many such places is impregnated with petroleum and the cracks partially filled with it. The areas of altered shale are almost invariably situated in the vicinity of oil seepages, which usually denote a fractured condition of the rocks such as would allow fire to spread and be supported. The observance of fires actually in progress in the shale and the changes that have taken place in the neighboring rocks—changes in every way similar to those in localities where no fire exists at present—give the best clues to the manner in which the shale has been baked in other places. It is difficult to conceive another source of heat sufficient to cause local baking of the shale in otherwise unaltered strata at a depth of 1,000 feet below the surface in such a case as has been mentioned. Probably there, as on the surface, it was due to ignition of bituminous material. It is probable that fire started in the petroliferous shale at the surface and threaded its way downward along cracks partially filled with bitumen. The failure to smother the fire in the shale on Graciosa Ridge, previously noted, indicates that such fires are able to survive with a small air supply. On the other hand, if the above theory is correct, it indicates that a considerable amount of oxygen may be present in the rocks at such a depth.

In this connection it may be mentioned that the temperature in a well near the one in which the burnt shale was found was 152° F., at a depth of 3,600 feet. The cause of ignition may be kindled fires, lightning, or the spontaneous combustion of the hydrocarbons or

[a] Explorations and surveys for the Pacific Railroad, vol. 7, 1857, pp. 65–72.

surface vegetation. Many of the recent cases of burning are directly traceable to the first cause, but for those which may have taken place before the advent of man either the second or third cause will have to be invoked.

RANGE IN TIME OF THE PHENOMENON.

As already mentioned, the marked influence of the hardened shale on the topography in certain places indicates that it originated in those places a long time ago. The age of some of the burnt shale is further shown by the presence of numerous fragments of it at a depth of at least 10 feet below the surface in horizontal beds of Pleistocene age. These beds consist of sand, clay, and rough gravel, and form the low hills between Guadalupe Lake and the high hills to the west. The fragments of shale are little worn and evidently of local derivation, having possibly come from the cliffs already mentioned south of Guadalupe. The fact that the Monterey shale has undergone this kind of baking in Pleistocene as well as in recent time indicates further that the accumulation of the oil and its dissemination in the surface rocks took place, or were taking place, before the latest orogenic movements in this coastal region.

FERNANDO FORMATION (MIOCENE-PLIOCENE-PLEISTOCENE).

GENERAL STATEMENT.

The name Fernando was first applied by Homer Hamlin to a series of rocks overlying the Monterey in the San Fernando Valley, Los Angeles County. The formation has since been recognized by Eldridge and Arnold[a] in the region of the Puente Hills, Los Angeles, and Santa Clara Valley oil districts, where it is a series of unaltered sedimentary rocks lying unconformably over the Monterey, and probably representing a portion of upper Miocene time, the whole of the Pliocene, and a part of the Pleistocene. Its lower portion is the equivalent of the Santa Margarita and Pismo formations, and its upper portion is contemporaneous with the Paso Robles formation, as these three are described by Fairbanks in the San Luis folio.[b]

In the region at present under discussion the name Fernando is applied to a similar formation that represents a large part of the Pliocene and probably includes the upper Miocene and part of the lowest Pleistocene. It consists throughout of a series of sandstone, conglomerate, and shale resting unconformably upon the Monterey. Unconformities also exist locally within the Fernando. It attains a thickness of at least 3,000 feet, but no one section exposes the whole series and it is probable that the formation includes a considerably greater thickness. It is widespread in the northern part of Santa

[a] The Santa Clara Valley, Los Angeles, and Puente Hills oil districts, southern California: Bull. U. S. Geol. Survey No. 309, 1907, pp. 22-28.

[b] Geologic Atlas U. S., folio 101, U. S. Geol. Survey, 1904..

Barbara County, where it was deposited in the old basin between the Santa Ynez and San Rafael ranges. It covers up the Monterey over the greater part of the basin, and as its structure in most places there conforms approximately to that of the Monterey, it is a fairly good key to the folding that has taken place in this underlying formation. The relation between the Monterey and Fernando is of a somewhat perplexing nature. An unconformity in dip between the two was not to be definitely made out on examination of the exposed contact in any part of the central basin, because of the fact that the Monterey and Fernando were subjected practically to the same movements over a large part of the region. Lithologic similarity of parts of the Fernando to the Monterey is also an obstacle to their differentiation. But pebbles of Monterey shale and flint, showing here and there pholas borings and giving evidence of marine deposition, are abundant in the Fernando. In fact, the greater part of the coarse detrital material of the Fernando conglomerate is derived from the Monterey, proving that its period of deposition was one of erosion in the previously deposited shale, that it followed the uplift above sea level of a portion of the Monterey, and that it was subsequent to the formation of the flint in that shale series. The importance of the break between the two is indicated by the change in character of the deposits from organic, probably deep-water sediments almost free from erosional débris to sandy and gravelly deposits derived from the wearing away of hard land areas. This change was hardly as marked as that occurring in the reverse order at the close of Vaqueros time, although it accompanied what was probably a greater time and structural break. The apparent structural conformity between the Monterey and Fernando at most places within the basin region is probably due to the previously almost undisturbed attitude of the shale upon which the Fernando was laid down and the subsequent disturbance of both formations at the same time. But remnants of the Fernando left around the border exhibit less conformity with the underlying Monterey, owing doubtless to the fact that the shale of the latter was upheaved around the edges of the basin to form the mountains bordering it during the period intervening between the close of Monterey time and the beginning of deposition of the Fernando.

The chief importance of the Fernando in connection with studies of this oil field is derived from the facts that it hides the oil-bearing formation over a wide area; that it affords through its structure, however, a clue to the structure of the underlying Monterey; and that it acts as a reservoir for oil (Arroyo Grande field) and as a receptacle for escaping bituminous material. In the last-mentioned way it gives origin to asphalt deposits of economic value and to cappings of hard asphalt that may be of significance as an aid in the retention of the oil within the Monterey.

LITHOLOGIC CHARACTER.

This formation is mapped as a unit, although it certainly represents a long period during which sedimentation, continuous in the region as a whole, was locally intermittent and carried on under differing conditions, owing to the differential elevations to which the region was subjected. The stratum resting upon the Monterey in one place is apt to be absent in another, where an overlap of one or another stratum may occur. The lowest recognized Fernando rocks occur south of Sisquoc, where the Monterey is overlain by a bed of brecciated and waterworn shale derived from it and cemented by argillaceous sand, above which lies about 200 feet of fine sand, succeeded by a 50-foot layer of diatomaceous shale that is indistinguishable from that of the Monterey. Above this shale the series grades up through about 600 feet of fine white and yellow sand and coarse sand, until a bed of conglomerate is reached. At other places, as south of Waldorf and south of Harris, the lowest stratum found at Sisquoc is either wanting or of minor importance, and beds of diatomaceous shale lie conformably over the Monterey shale, making the dividing line very hard to find. West of Waldorf the contact is marked for miles by a bed of brecciated Monterey shale of coarse and fine fragments, in places cemented into a hard amalgam by a paste of bituminous material. Here the overlying beds are made up of fine shale and sand and pebbly sandstone, which, though actually separated by an important unconformity from the Monterey, as indicated by the brecciated zone and the abundance of pebbles of that formation in them, are conformable in dip with the underlying beds. A still younger series of fossiliferous shale and sand marks the base of the Fernando 1½ miles northeast of Divide, and also northeast of Schumann and northwest of Mount Solomon; and on the summit of the ridge in the vicinity of the head of Pine Canyon, halfway between the two latter localities, the Monterey is capped by what appears to be a part of the same series somewhat younger still. This shows that at the locality near the head of Pine Canyon either an overlap of the late Fernando occurred on an old eminence of Monterey shale that was above the sea at the time of the deposition of the part of the Fernando immediately preceding, causing the omission on its summit of hundreds of feet of sediments which were deposited around its base; or else the portion of the Fernando preceding this series was removed from above the Monterey during a period of erosion within Fernando time, this period being followed by subsidence.

Along the ridge 1 mile southeast of Redrock Mountain, in the Purisima Hills, there is a capping of diatomaceous shale resembling that of the Monterey in every respect, but containing characteristic Fernando fossils. It was not suspected that this shale belonged to a formation distinct from the Monterey until the fossils were found.

It would be difficult to work out the limits of the area that this remnant covers. In all probability it is very small, and it has not been shown on the map. This shale here forms the base of the Fernando. A pebbly layer with constituent well-worn pebbles of Monterey shale embedded in sand has aided in the accumulation of asphalt on the summit of the ridge near by, where it probably marks the basal line of the Fernando formation.

Above the soft diatomaceous or gritty shale and fine white sand that is common at or near the bottom of the Fernando the bulk of the formation is composed of rather loosely consolidated fine white and yellow sand and coarser gray sand that grades here and there into thick beds of loose conglomerate. The conglomerate is made of well-worn pebbles, mostly of flint and hard shale, embedded in a coarse sandy matrix. Locally the sand and conglomerate are extremely hard, owing usually to the presence of a large number of mollusk shells from which a calcareous cement has been derived. The most prominent bed of conglomerate, and one that seems to be constant over the whole region, occurs from 800 to 1,000 feet up in the series (above the lowest horizon) just north of Canada de los Alisos, on La Laguna grant. What is probably the same bed is well exposed in cliffs west of Canada Laguna Seca, 1½ miles south of the Los Alamos Valley. This loose aggregate of sand and pebbles in alternating strata of coarse and fine material is dominantly composed of the light-colored pebbles of Monterey shale. Pebbles of other varieties occur more sparingly. Above the conglomerate lies a stratum of limestone that is constant over the whole region and seems to mark a division in the Fernando. There are two or more massive beds of hard limestone interbedded with soft, gray, very alkaline, earthy material, making a total thickness ranging from 10 to perhaps 50 feet. Its fossils indicate that it is of fresh-water origin, and possibly it marks the base of a fresh or brackish water series. The portion of the Fernando overlying this limestone probably corresponds to the fresh-water Paso Robles formation of the Salinas Valley described by Fairbanks in the San Luis folio. In some places where this higher portion of the Fernando above the limestone has not been worn away, it is found to consist of little-consolidated beds of fine sand, gravel, and clay that look as if they might have been laid down in fresh water, but no proof of their origin has been found. Such beds are well exposed in the foothills of the San Rafael Range north of Santa Ynez, where they weather characteristically into cliffs at the summit of hills. A view of such an exposure is given in Pl. VI, *A* (p. 46), which affords a good idea of the rough alternating beds of coarse material. No good lithologic or paleontologic criteria are known by which this series may be separated from the lower portion of the Fernando, and they are therefore mapped as a unit.

STRUCTURE.

As has been stated, the Fernando is generally so nearly conformable with the Monterey that it is difficult to draw a line between them on the basis of a discrepancy in dip. Nevertheless, it is in general true that folding has been gentler in the Fernando than in the Monterey. It would seem that the older formation had been disturbed in varying amounts, in some places severely and in others gently, during the process of uplift that put an end to its period of deposition. As a result the dips at the present time in the Fernando are apt to be less steep than in the Monterey, but folding has gone on largely along old lines, so that conformity in strike between the two formations is the rule.

Wide, low folds are characteristic of the structure in the Fernando within the Santa Maria basin region. This is illustrated by the broad anticlines in this formation in the Solomon Hills, the broad anticline in the Purisima Hills, and the synclines in the Los Alamos and Santa Rita valleys, in which the dips range from 5° to 25° as a rule for a long way on either side of the fold and rarely become steeper than 30° or 35°. In places, as south and west of Sisquoc and west of Canada Laguna Seca, the beds are almost if not quite horizontal, but this is exceptional. Curves and plunges in the preexisting low folds in the Monterey gave rise to structural basins in which the Fernando was deposited as a filling. Such was the origin of the oval area of Fernando sand covering the eastern portion of the Todos Santos y San Antonio grant. This basin is the westward extension of a great synclinal basin that runs from that locality first eastward and then southeastward across the Los Alamos, La Laguna, and Corral de Quati grants and has determined the position of the Los Alamos Valley. The northern arm of this syncline slopes gradually up to the axis of the Solomon Hills, and the southern arm rises abruptly into the Purisima Hills, the slope on both sides conforming with the topography. The region of low slopes covered by parts of the Mission La Purisima and Santa Rita grants is a somewhat similar wide synclinal basin filled with soft Fernando sediments. The Fernando is steeply upturned along the northeastern border of the Casmalia Hills, where it stands almost vertically in contact with much disturbed and in places overturned beds of the Monterey shale. It is upturned also where it rests against the serpentine north of Alamo Pintado Creek on the La Laguna grant, and southwest of Los Alamos it seems to dip very steeply under the brow of an overturn in the Monterey. In the San Rafael Mountains patches of Fernando deposits occur as remnants, and the beds in many places are steeply folded or turned completely on edge. They exhibit unconformity with the Monterey. In at least three places the Fernando is affected by faulting—a few miles west of Los Alamos, in the neighborhood of Cebada Canyon, and along the fault

crossing Labrea Creek. In the first two the dip of the beds is moderate and the disturbance is not great.

DISTRIBUTION.

An idea of the distribution of the Fernando may be well obtained from the map (Pl. I, in pocket), as it is not covered by so many formations as the older series. It is much more widespread near the surface, however, than appears on the map, since it is probably present and hidden by only thin deposits over a great part of the area mapped as terrace deposits and alluvium.

The general character of the Fernando is that of a filling. Its soft, loose, spreading sands, which preserve poorly evidence of low folds, form moundlike hills and broad valleys that convey the idea of a filled topography. But, on the other hand, harder beds and surface cappings due to hardening by iron oxide, which not uncommonly produce sharp, square outlines, are marked features of the topography, as in the vicinity of Mount Solomon, at the head of Howard Canyon. On the northeastern border of the Casmalia Hills, between Schumann and Graciosa Canyon, a lime-hardened sandstone predominates and forms a prominent ridge. In the Santa Rita Hills the lines of structure that there curve around from a westerly direction to the southeast are brought out by the resistant limestone which supports the northeast flanks of the hills. The wide-stretching foothills of the San Rafael Range north of Santa Ynez have a character all their own. They are formed of gravel, clay, and sand that have the appearance of belonging to a fresh or brackish water series, and they stand out with many bold faces that have been cut in the soft formation, as illustrated in Pl. VI, *A*. Elsewhere the dominant character of the Fernando and its topographic forms are due to the soft sand which forms the major portion of the series.

EVIDENCE OF AGE.

At least five and probably six distinct horizons are recognizable in the Fernando by means of characteristic fossil faunas. The localities at which these different faunas occur, named in their probable relative order, beginning with the oldest, are as follows:

(*a*) South of Waldorf in soft shale; south and east of Sisquoc in fine sandstone.

(*b*) "Sea-urchin bed," Squires (Santa Maria Oil and Gas) lease; California Coast lease; south of Graciosa-Western Union wells; west of Harris Canyon; vicinity of Hill wells in the Lompoc field; and near head of Howard Canyon.

(*c*) Waldorf asphalt mine, railroad cut 1 mile northeast of Schumann; Pennsylvania asphalt mine at east end of Graciosa Ridge; all in gray shale or fine gray sandstone.

(*d*) Waldorf asphalt mine; railroad cut 1 mile northeast of Schumann; Fugler Point asphalt mine; Sisquoc (or Alcatraz) asphalt mine; and points along north flank of Casmalia Hills, in coarse sandstone or conglomerate.

(*e*) East end of Folsom lease in soft sandstone.

(*f*) Fresh or brackish water beds immediately west of the mouth of Canada Laguna Seca.

The beds at horizon *a* are of marine origin, are probably upper Miocene in age, and correspond in a general way to Fairbanks's Santa Margarita and Pismo formations. Those at horizons *b*, *c*, *d*, and *e* are of marine origin, are closely related, belong at the base of the Pliocene, and are in a general way the equivalents of the middle Purisima and lower and upper San Diego formations. At horizon *f* are beds of fresh-water origin, probably representing Fairbanks's Paso Robles formation and Lawson's marine Merced formation.

The following is a list of the fossils obtained from the Fernando:

Fernando (upper Miocene-Pliocene-Pleistocene) fossils from the Santa Maria district, California.

	4469	4471	4472	4473	4474	4475	4476	4477	4481	4485	4486	4487	4488	4489	4490	4491	4492	4506	4523
Actæon sp.																X			
Amphissa (?) sp				X															
Angulus sp				X															
Arca sp. a				X															
Arca sp. indet										X				X					
Arca trilineata Conrad (Pl. XXIV, fig. 5)		X	X	X	X	X						X						X	X
Astyris richthofeni Gabb (Pl. XXIV, fig. 3)				X	X		X		X										
Balanus cf. concavus Bronn					X		X												
Bathytoma carpenteriana Gabb var. fernandoana Arnold (Pl. XXIII, fig. 7)							X												
Bathytoma cf. tryoniana Gabb				X															
Bittium arnoldi Bartsch				X															
Bittium casmaliaensis Bartsch				X															
Cadulus fusiformis Sharp and Pilsbry (Pl. XXI, fig. 8)				X															
Calliostoma sp. indet				X	X														
Callista subdiaphana Carpenter			X	X		X							X						X
Cancellaria sp. a			X	X		X													
Cancellaria crawfordiana Dall var. fugleri Arnold (Pl. XXI, fig. 9)						X													
Cardium meekianum Gabb					X	X										X			
Cardium sp. indet		X																	
Chione sp																X			
Chlorostoma (?) sp		X																	
Chrysodomus sp							X												
Clidiophora punctata Carpenter (Pl. XXIII, figs. 2, 3)							X												
Crepidula princeps Conrad (Pl. XXIV, figs. 1, 2)		X		X		X				X			X			X		X	X
Crucibulum spinosum Sowerby					X														
Cryptomya ovalis Conrad (Pl. XXII, fig. 7)		X				X			X	X				X					
Cumingia californica Conrad (Pl. XXIII, fig. 5)						X													
Dosinia ponderosa Gray (Pl. XXII, fig. 8)		X				X				X					X				
Drillia graciosana Arnold (Pl. XXI, fig. 18)			X																
Drillia johnsoni Arnold (Pl. XXI, fig. 13)				X															
Drillia waldorfensis Arnold (Pl. XXI, fig. 12)				X															
Echinarachnius ashleyi Merriam (Pl. XXIV, figs. 6, 7)	X								X		X	X							
Echinarachnius cf. excentricus Eschscholtz var. (Pl. XXIV, fig. 8)					X											X			
Fusus sp. a		X	X																
Fusus sp. b										X									X
Galerus inornatus Gabb						X				X									
Glycymeris cf. barbarensis Conrad					X	X				X									
Kennerlia (?) sp			X	X															
Leda orcutti Arnold (Pl. XXII, fig. 9)			X	X	X								X						
Leda taphria Dall (Pl. XXII, figs. 3a, 3b)				X															
Lucapina cf. crenulata Sowerby						X													
Lunatia lewisii Gould (Pl. XXI, fig. 3)		X		X	X	X													

Fernando (upper Miocene-Pliocene-Pleistocene) fossils from the Santa Maria district, California—Continued.

	4469	4471	4472	4473	4474	4475	4476	4477	4481	4485	4486	4487	4488	4489	4490	4491	4492	4506	4523
Lymnæa alamosensis Arnold (Pl. XXI, figs. 6, 7) [a]																			
Macoma nasuta Conrad (Pl. XXII, fig. 5)		X		X	X		X			X									X
Macoma sp				X															
Macoma cf. secta Conrad					X														
Mactra sp						X	X			X									
Miopleiona oregonensis Dall				X		X													
Modiolus rectus Conrad				X	X	X				X									
Monia macroschisma Deshayes					X														
Muricidea sp					X														
Mya truncata Linné				X															
Mytilus sp. indet					X														
Nassa californiana Conrad (Pl. XXIV, fig. 4)		X			X	X	X	X	X	X						X			
Nassa waldorfensis Arnold (Pl. XXI, fig. 17)				X	X														
Natica clausa Broderip and Sowerby (Pl. XXI, fig. 16)				X	X	X													
Neverita recluziana Petit (Pl. XXI, figs. 14a, 14b, 15)					X	X	X												
Ocinebra lurida Middendorf					X														
Ocinebra micheli Ford var. waldorfensis Arnold (Pl. XXI, fig. 10)				X															
Olivella biplicata Sowerby					X		X												
Olivella cf. intorta Carpenter									X										
Opalia anomala Stearns				X	X														
Opalia varicostata Stearns				X	X														
Ostrea veatchii Gabb (Pl. XXIII, fig. 10)				X	X														
Ostrea possibly veatchii Gabb			X																
Panomya cf. ampla Dall						X													
Panopea generosa Gould		X		X	X	X													
Pecten (Plagioctenium) near cerrosensis Gabb						X													
Pecten (Patinopecten) healeyi Arnold (Pl. XXVI, figs. 1, 2)					X							X							
Pecten (Pecten) hemphilli Dall (Pl. XXV, fig. 5)					X														
Pecten (Chlamys) lawsoni Arnold (Pl. XXV, fig. 3)			X	X	X	X													
Pecten (Patinopecten) oweni Arnold (Pl. XXV, figs. 2a, 2b)										X								X	
Pecten (Pecten) stearnsii Dall (Pl. XXV, figs. 1a, 1b)						X													
Pecten (Chlamys) wattsi Arnold (Pl. XXV, fig. 4)						X													
Phacoides annulatus Reeve (Pl. XXIII, fig. 8)		X	X	X	X											X			
Phacoides intensus Dall (Pl. XXIII, figs. 9a, 9b)				X	X														
Phacoides nuttallii Conrad var. antecedens Arnold (Pl. XXII, fig. 6)		X					X		X										
Pholadidea ovoidea Conrad (Pl. XXII, figs. 1a, 1b)			X	X		X	X												
Pholadidea (?) sp. indet																		X	
Platyodon cancellatus Conrad var					X														
Pleurotoma (Borsonia) sp. a				X															
Pleurotoma sp. b						X													
Priene oregonensis Redfield var. angelensis Arnold (?)					X														
Priene oregonensis Redfield (Young) (Pl. XXI, fig. 2)				X															
Purpura crispata Chemnitz (Pl. XXII, fig. 2)					X														
Saxidomus gracilis Gould					X														
Saxidomus (?) sp. a										X									
Scala sp. a					X														
Sigaretus debilis Gould		X																	
Siliqua cf. edentula Gabb		X																	
Solen cf. sicarius Gould				X	X	X	X												
Spisula catilliformis Conrad var. alcatrazensis Arnold (Pl. XXIII, fig. 6)		X																	
Spisula sisquocensis Arnold (Pl. XXIII, fig. 1)		X																	

[a] Fresh-water beds in the Fernando formation, 1 mile southeast of bench mark 425, Los Alamos Valley.

Fernando (upper Miocene-Pliocene-Pleistocene) fossils from the Santa Maria district, California—Continued.

	4469	4471	4472	4473	4474	4475	4476	4477	4481	4485	4486	4487	4488	4489	4490	4491	4492	4506	4523
Tapes cf. lacineata Carpenter		×			×		×												
Tapes staleyi Gabb		×			×					×									×
Tapes tenerrima Carpenter (Pl. XXII, fig. 10)		×				×	×	×											
Tellina sp		×		×															
Tellina aff. bodegensis Hinds													×						
Terebratalia occidentalis Dall (Pl. XXII, figs. 4a, 4b)						×													
Thalotia caffea Gabb (Pl. XXI, figs. 4, 5)						×													
Thracia cf. trapezoides Conrad						×													
Thyasira aff. gouldii Philippi				×															
Tresus nuttallii Conrad					×											×			
Tritonium sp. indet				×															
Trochita radians Lamarck (Pl. XXI, fig. 1)						×													
Trochita sp. indet																		×	
Turritella cooperi Carpenter (Pl. XXI fig. 11)			×	×	×														
Venericardia californica Dall (Pl. XXIII, fig. 4)			×	×	×	×													

4469. One hundred yards northeast of California Coast oil well No. 3, 1 mile east of Divide, and 3 miles southeast of Orcutt.
4471. Alcatraz asphalt mine, 3 miles east of Sisquoc.
4472. Pennsylvania asphalt mine, 3½ miles southeast of Orcutt.
4473. Waldorf asphalt mine, 3 miles south-southeast of Guadalupe.
4474. Railroad cut 1 mile north of Schumann station.
4475. Fugler Point asphalt mine, 1 mile north-northeast of Gary, at head of Santa Maria Valley.
4476. Asphaltum layer above Monterey shale, near Folsom well No. 3, Santa Maria oil field, 3 miles southeast of Orcutt.
4477. Near Folsom well No. 4, Santa Maria oil field, 2½ miles southeast of Orcutt.
4481. Five miles N. 30° E. of Lompoc bench mark 95, in prominent sandstone beds around Purisma oil wells.
4485. One-half mile south of Sisquoc.
4486. *Echinarachnius ashleyi* horizon, immediately west of Santa Maria Oil and Gas Company's well No. 4, 2 miles southeast of Orcutt.
4487. Immediately east of head of Howard Canyon, 4 miles north-northeast of Los Alamos. *Echinarachnius ashleyi* horizon.
4488. On ridge south of road about 2¼ miles northwest of Blake.
4489. Southeast side of La Zaca Creek, where it empties from steep canyon; at base of asphalt sandstone in shale, 8 miles north of Los Olivos.
4490. Four miles east-northeast of Los Alamos, on Cuaslui Creek.
4491. Gully 2¼ miles west-northwest of Blake.
4492. One and three-fourths miles S. 5° W. of bench mark 425 of Los Alamos Valley, one-half mile northwest of sink on top of ridge.
4506. One mile southeast of summit of Redrock Mountain, along ridge, near 1,700-foot knob.
4523. One mile due south of Sisquoc, in ravine.

QUATERNARY.

GENERAL STATEMENT.

Three distinct classes of Quaternary deposits younger than the latest Fernando can be differentiated in this region, although it is difficult to distinguish between them areally. They are terrace deposits, dune sand, and alluvium, each one of which as mapped may possibly represent more than one period of deposition. They are deposits of comparatively little thickness laid down unconformably upon the older formations subsequent to the greater part of the disturbance and deformation that has affected the region.

TERRACE DEPOSITS.

GENERAL DESCRIPTION.

Terraces are common in this region and are among the most prominent topographic features. They are fairly even surfaces, invariably

inclined slightly toward the ocean or the line of drainage, and ranging in size from tens of square miles to only a few feet square. The more extended terraces fringe the coast line and the larger valleys and cover areas of low hills. The smaller ones are scattered over ridges and hilltops and along the smaller valleys. These terraces are covered with a thin coating of sand and gravel, and here and there with clayey material. The distribution of the deposits is well shown on the map, with two general exceptions. In the first place, many of the strips of land along valleys mapped as covered with terrace deposits may not represent true terraces, as it is almost impossible to draw definite distinctions between such horizontally bedded valley fillings, true terrace cappings, and recent alluvium. All post-Fernando deposits in small valleys are therefore mapped with the terrace formation, and alluvium is shown only in the extended valley bottoms, where dividing lines between it and the terrace deposits are drawn arbitrarily. In the second place, owing to the lithologic similarity of the Fernando and the terrace-deposit sand and the similar surface appearance of these two formations, the attempt has been made to represent on the map only a few areas of the terrace sand overlying the Fernando. The Fernando is doubtless capped by terrace deposits in many places, but it is usually impossible to tell whether this is true or not. The lines of contact between these formations are of necessity arbitrarily shown.

This similarity causes much difficulty in places in determining whether the deposits belong to the Fernando or to the later epoch, and whether it is necessary to go through a great thickness of Fernando beds or only a few feet to reach the Monterey below. Where fossils, distinct lines of bedding, or tilted strata are present they are indications that the sand belongs to the Fernando.

The terraces are found commonly at all altitudes up to 1,200 feet, and a few even as high as 1,400 feet. None have been definitely recognized at a higher elevation.

LITHOLOGIC CHARACTER.

The material of the terrace deposits is usually sand and conglomerate, for the most part the former. The sand is medium grained and contains scattering waterworn pebbles. It is normally soft and grayish, but in many places compact, being stained a reddish yellow and hardened by iron oxide or filled with iron-stained concretions. In this surficially compacted state it forms hard cappings on hilltops and slopes. Round, bullet-like, iron-hardened concretions are characteristic of the derived soil. Over much of the surface of Burton Mesa and in other places this deposit occurs as loose, grayish sand, hardened locally by the action of rain water and various salts or oxide of iron. The conglomerate—or gravel, as it might equally well

be called—is composed of bowlders, pebbles, and fragments of Monterey flint and shale, besides pebbles of other rocks in smaller quantity. Some of the pebbles are very much waterworn, but in places the number of unworn fragments of shale almost necessitates the use of the word "breccia" in describing the deposits. Evidence of bedding is rarely prominent in the typical terrace deposits, but they invariably appear to lie horizontal, seeming to have been little disturbed by the uplift of the land that brought them to their present elevation.

No fossils have been found in these deposits, but they contain numerous pholas-bored pebbles of Monterey shale, and in places, as on Burton Mesa, the Monterey shale itself, upon which the deposits lie, has been bored by these marine mollusks.

Many of the cappings formed parallel with the surface through hardening by iron oxide have the appearance of being beds with appreciable dip, and are therefore misleading. The thickness of the coating of Burton Mesa is 25 or 30 feet and the cover of the typical terrace in other parts of the region has about the same thickness. Whether it attains a much greater development than this at any place is hard to tell. These shallow coverings hide considerable areas of the Monterey and obscure its structure, but most of the canyons that cut into the terraces reveal the presence of the oil-bearing formation beneath. The thickness of the coatings is not sufficient to make a serious difference in the depth to which it is necessary to drill for oil. The deposits are economically of importance as reservoirs for the oil escaping from the Monterey shale, and thus they give rise to accumulations of asphalt. It is usually impossible to tell whether the sand that helps to form the asphalt is a terrace deposit or belongs to the Fernando. The terrace sand can not form as deep asphalt deposits as those due to the Fernando sand.

In some of the valley fillings above mentioned, as for instance along Salsipuedes Creek, and at the west edge of the Santa Maria Valley between Guadalupe Lake and the Casmalia Hills, there occur horizontally bedded deposits of clay, sand, and gravel differing in appearance from the terrace deposits and possibly differing in age and origin. A good example of an old valley filling which now forms the summit of a hill is shown in Pl. IV, *B* (p. 36). It consists of a sandy and earthy material through which rock fragments and pebbles are scattered. It illustrates the usual unconformity of the post-Fernando deposits with the older formations. The low hills in the region of Santa Ynez are formed largely of horizontal beds of fine gravel unlike the Pleistocene deposits found elsewhere. These exhibit in one place an appearance of being tilted, though this may be due to cross-bedding.

ORIGIN.

Most of the terrace deposits are probably of marine origin. This is proved in the case of the most typical deposits by the presence of the pholas borings already mentioned. The deposition was carried on in shallow water and much of the material was derived on the spot from the wearing away of the shore line of Monterey shale, the fragments of which were not always subjected to much polishing before being deposited and protected from agencies of erosion. These deposits give undeniable evidence of a great uplift of the coast during Pleistocene time. It seems most probable that the terraced surfaces resulted from marine planation along gradually rising shore lines and that the formation covering them represents the beach and shore deposits. The rise of the land was probably too rapid and the amount of sediment too small to allow much off-shore extension of the deposition. The material that may have been deposited in the deeper places determined by the depressions in the topography has since probably been largely removed by erosion. The terrace deposits themselves have been extensively eroded and in many places are left as mere remnants. Some of them have no doubt been subsequently added to by wind-blown sand.

It is probable that some of the terraces and horizontal Pleistocene deposits along valleys have been formed by streams. Most of the valley fillings were probably laid down in this way. At the mouths of some canyons, as along the western side of Graciosa Canyon, Pleistocene deposits have been built up in the shape of detrital fans, which have since been carved into flat-topped, steep-sided blocks by recent streams.

DUNE SAND.

The prevailing northwesterly wind from the ocean has amassed great deposits of sand in places along the coast. The process has probably been going on all through the Quaternary period and it is hard to distinguish the older of the eolian deposits from those partially or entirely of marine deposition. The line of contact of these formations as mapped is arbitrary.

The greatest mass of dune sand occurs at the northwest end of the Casmalia Hills, where the gradual slope down to the sea from an elevation of about 1,200 feet is covered by loose, yellow sand of probable eolian origin. This drifts about incessantly and is probably still in the process of collecting, being supplied from the long, low, open shore to the north and held in check by the bulwark of the Casmalia Hills on the south. This deposit has a thickness of several hundred feet. At its base along the coast is exposed a basal layer of large bowlders and horizontally stratified sand. The original slope of the

hills was probably at least partly covered during the uplift of the coast by marine terrace deposits similar to those found elsewhere in the region, these being later buried by the gathering wind-blown sand. Recent marine shells are widely scattered over the surface of this sand, but are not considered by the writers as indicating its marine origin. They were probably carried there by Indians or birds.

South of the Casmalia Hills, where the coast is open to the winds, sand dunes are continually forming and covering up the terrace deposits. The sand is not retarded by an inland barrier, however, as on the north of the hills, and no such vast deposit has been formed. The sand is continually being carried into the interior valleys and spread thinly over a wide area.

ALLUVIUM.

All the valleys of this region contain a certain amount of alluvial material and stream gravels, which reach in many localities a thickness of 50 feet or more. In some places the deposit is earthy, in others sandy earth, and in still others pure sand, gravel, or clay. It is as a rule horizontally stratified. Recent deposits of this character attain considerable extent in the wide valleys, but it is not easy to distinguish them from Quaternary deposits of different age or of somewhat different origin. They are mapped as distinct only in the larger valleys and the contact lines are arbitrary. Practically all the hills and valleys within the territory mapped have a covering of soil.

IGNEOUS ROCKS.

GENERAL STATEMENT.

The formations in this region are chiefly of sedimentary origin, but eruptive and intrusive igneous rocks of various ages appear. These are all basic in composition. Layers of volcanic ash high in silica interbedded with the Monterey are discussed with the sedimentary series (p. 37). The center for igneous rocks is in the region around Point Sal of which Fairbanks made a special study, and the statements here made in regard to the igneous rocks of that region are based largely on his description.[a]

IGNEOUS ROCKS OF PRE-MONTEREY AGE.

Fairbanks describes a small intrusion of basalt having a laccolithic appearance in the Knoxville (lower Cretaceous) shales north of Mount Lospe, in the Casmalia Hills, and a large neighboring area of spheroidal basalt that he is certain is older than the Monterey

[a] Fairbanks, H. W., The geology of Point Sal: Bull. Dept. Geology, Univ. California, vol. 3, 1896, pp. 1-92.

and believes to antedate the Knoxville. It is closely associated and intermingled with bodies of diabase and gabbro. This complex forms Point Sal Ridge and the rocky headland of Point Sal. Another complex that he believes belongs in the Knoxville forms a long dike north of Schumann Canyon. It is an exceedingly complicated intrusive mass of gabbro and peridotite that has been penetrated by later dikes of diabase, norite, gabbro, and intermediate types of rock.

The areas mapped as Franciscan (Jurassic) are largely occupied by serpentine that was originally intruded in Franciscan strata. This serpentine may be older than the Knoxville, and the last-mentioned occurrence of gabbro and peridotite may be contemporaneous with it.

Diabase was struck at a depth of 1,300 feet in the Pezzoni well No. 1, southwest of Sisquoc. It is a considerably altered rock composed largely of serpentine and plagioclase feldspar, with some augite, possibly a small amount of unaltered olivine, considerable magnetite, and several accessory minerals. This occurrence is of considerable importance as affecting the prospects for the production of oil in this neighborhood. The question arises whether this diabase has intruded the Monterey, as in the San Rafael Mountains, or whether it is a part of the older igneous formations, in which diabase is common. The fact that the rock is so much altered probably indicates that it belongs to a formerly exposed older formation upon which a fairly high portion of the Monterey shale series has overlapped. It is hardly conceivable that an intrusion at such a depth in the shale could have undergone so much alteration. In either case, whether this diabase marks the base of the Monterey or whether the shales have been intruded by an igneous mass, the conditions are unfavorable for the discovery of oil in the immediate vicinity.

IGNEOUS ROCKS INTRUDING THE MONTEREY.

The youngest igneous rocks occurring in the Santa Maria quadrangle and those of chief interest in the present connection are intrusive in the Monterey (middle Miocene). Such are five small areas of diabase mapped by Fairbanks south of Point Sal and two areas of diabase in the San Rafael Mountains. The age of the two latter is somewhat in doubt, but the metamorphic and disturbed appearance of the Monterey shale in their vicinity indicates that they originated as dikes intruding the Monterey. The shale appears hardened and baked in the immediate neighborhood and narrow tongues of Monterey shale, certainly altered along the contact, extend into the mass on Tepusquet Creek. Along its edges appear patches of *Aucella*-bearing sandstone belonging to the Knoxville, which were probably brought up from below by the intrusion. The diabase in both areas is of dark-green color and coarse texture and exhibits sheared serpentinous facies.

Another intrusion of probable post-Monterey age forms a single outcrop in the hills 7 miles northeast of Point Conception. It is a dike of basic porphyry related to basalt. On one side of the outcrop the bases of horizontally lying rough pentagonal columns are well exposed. It is not known whether the sedimentary rocks through which this is intruded belong to the Monterey or the upper part of the Vaqueros.

GEOLOGIC HISTORY.

EARLIEST PERIODS.

The general geologic aspect of the Santa Maria district is that of a region of comparatively recent geologic formations. Tertiary rocks, in places covered by Pleistocene deposits, are predominant, those of Cretaceous and Jurassic age less widespread, and older formations entirely absent. The Tertiary has received almost all the attention in the present study and little can be said of the history of the region previous to that period. The much-disturbed and metamorphosed Jurassic sediments (Franciscan), intruded by serpentine, form the basement of the whole region, but outcrop only very locally. In Cretaceous time a considerable thickness of marine sediments was laid down, but these deposits were probably not greatly disturbed before the beginning of deposition in the Tertiary. To the present time they have remained unmetamorphosed and no more affected by mountain-making forces than later formations. Igneous intrusions, however, took place at different times in the Cretaceous.

EOCENE PERIOD.

All the greater divisions of the Tertiary, with the possible exception of the Oligocene, are represented by marine sediments, the major part of this time having been taken up by sedimentation. The relations between the Cretaceous and Eocene rocks have not been studied. Sedimentation began at some time in the Eocene not yet determined, in the southern portion of the region mapped, and continued nearly to the end of the Eocene, when it ceased for a period of unknown length. It was probably in the period just preceding that of the deposition of the Eocene sediments that the forces began to work which caused the structural features south of the region where the San Rafael Mountains now stand to assume an east-west trend. In this way may have been formed the depression extending east and west across the region now occupied by the Coast Ranges, which afforded a basin of deposition for the Eocene and possibly a connection between the ocean and the basins in which strata of the same age were deposited in the interior. A large part of the Santa Ynez Mountains is composed of Eocene strata which have been lifted up along east-west lines of structure. The main

uplift did not occur at the close of Eocene time, but it is probable that orogenic movements did bring to a close the period during which the Eocene sediments were laid down by raising the strata slightly above the sea and preventing for a time further deposition. How long this time was is not known, but it corresponds approximately with the Oligocene.

LOWER MIOCENE PERIOD.

The movements immediately following the deposition of the Eocene caused no appreciable disturbance in the Eocene strata, and when sedimentation recommenced over the same area in lower Miocene time neither the old nor the new strata preserved any positive evidence in their relative position that a time break had occurred. The great masses of coarse conglomerate forming the base of the lower Miocene portion of the group record a change to conditions of very shallow water, and the abrupt change of faunas indicates that a long time interval separated their deposition from that of the subjacent Eocene. It is most probable, however, that the post-Eocene movements, which were gentle, were also somewhat local, and that in portions of the Santa Ynez Mountains to the east of the region under discussion sedimentation was more nearly continuous. At about the close of the Oligocene period the Eocene basin was again depressed; deposition of sediments, almost entirely of detrital origin and very similar to those previously laid down, ensued in a widening area covered by the sea; and subsidence of the land gradually continued. The Vaqueros formation, which resulted from this period of depression, represents the greater part of lower Miocene time.

MIDDLE MIOCENE PERIOD.

The middle Miocene (Monterey) shale formation is one of striking individuality, and conditions of unusual character prevailed during its period of deposition. At the beginning of middle Miocene time the land sank over a large part of the region of California now occupied by the Coast Ranges and fairly deep water conditions became prevalent. The wearing away of extended land areas ceased as they became submerged, and the material for the formation of coarse detrital deposits was no longer plentiful. Two varieties of deposits, which were largely of organic origin, were the chief ones to be formed during the long period that followed. These were the laminated limestones and the much more abundant siliceous shales. Silt of extremely fine grain, both of siliceous and argillaceous nature, was swept into the sea waters, probably from considerable distances, and settled down to form a considerable proportion of the deposits; but sand and other coarse detritus found their way only at rare intervals

to the main portions of the quiet sea bottom which was formerly the surface of the land and which had been given a comparatively low relief by the long period of erosion that preceded the submergence.

During the period of transition between the Vaqueros and the Monterey, limestone was formed chiefly, but somewhat inclosed basins where deposits of alkaline mud were laid down apparently existed in places. Such a basin is indicated by the alkaline gypsiferous clays on the south side of the Casmalia Hills, probably representing upper Vaqueros. In some places, as, for instance, in the San Rafael Mountains, sandstone beds were formed early in Monterey time, probably in the neighborhood of locally unsubmerged areas. But later very little sand was deposited anywhere. Further submergence no doubt took place during the period, removing the sources of this sand and allowing to be deposited under fairly constant conditions a thickness of beds greater than a mile. It is not probable, however, that the depth of the sea was at any time as much as this, being more likely closer to half a mile.

During the early part of Monterey time conditions were variable, calcareous and siliceous deposits alternating, probably as a result of alternating temporary predominance in the sea of organisms with calcareous or siliceous shells. As the period progressed the siliceous organisms became more predominant and remained so, making up a large fraction of the total bulk of the Monterey formation. It was an age of diatoms. These small marine plants lived in extreme abundance in the sea and fell in showers with their siliceous tests to add to the accumulating ooze of the ocean bottom, just as they are forming ooze at the present day in some oceanic waters. It is well known that diatoms multiply with extreme rapidity. It has been calculated that starting with a single individual the offspring may number 1,000,000 within a month. One can conceive that under very favorable life conditions, such as must have existed, the diatom frustules may have accumulated rapidly at the sea bottom and aided the fine siliceous and argillaceous sediments in the quick building up of the thick deposits of middle Miocene time. A principal obstacle to the rapid accumulation of the diatoms might be the limited supply of silica from which these algæ derive the material of their tests. Other organisms with their shells and skeletons were also present to aid in building up the shale beds. They were Radiolaria and Foraminifera; sponges with their spicules, which were abundant; Crustacea; fishes, the remains of which are numerous in the shales; and mollusks with delicate shells, which are common, though poorly preserved.

Volcanic eruptions, possibly submarine, broke out at different times during the latter part of the lower Miocene (Vaqueros) and the early part of the middle Miocene (Monterey.) They may have accompanied movements that took place during the transition

period. Acidic volcanic ash of a rhyolitic type was ejected, and it settled in the ocean to form regular beds of considerable thickness and extent interstratified with the other sediments. The occurrence of ash interbedded with diatomaceous earth that probably belongs fairly high in the Monterey formation indicates that these eruptions did not cease in the early part of middle Miocene time. Neither the centers of eruptions nor any lava equivalents of the ash have been found in the field. Similar eruptions were characteristic of the lower and middle Miocene for long distances north and south of this region.

LATE TERTIARY AND EARLY QUATERNARY PERIOD.

The Monterey period of deposition was brought to a close by orogenic movements which folded the shales and lifted them above the sea in many places. In some regions the folding was intense, the greatest disturbances accompanying the uplift of the mountain ranges to an altitude of thousands of feet. The San Rafael Mountains, which were upheaved at this time, probably extended along the lines of former mountains, and some smaller mountainous or hilly areas likewise, such as the Casmalia Hills and perhaps portions of the Santa Ynez Range, followed former zones of uplift. But for the most part the Santa Ynez Range was probably new. It is doubtful whether it was ever completely covered by Monterey sediments, and its structure may have been determined by minor folding previous to the beginning of the Monterey, but it is probable that this range did not have any approach to its present proportions until after middle Miocene time. In other regions low, broad folds were formed during the post-Monterey disturbance and the strata were not upheaved to a great altitude; such was the case in parts of the basin region between the San Rafael and Santa Ynez mountains.

After the formation of the middle Miocene shales they were intruded at several different points by basic igneous masses, mostly of the nature of diabase. The disturbance which put an end to the period was profound and this igneous activity was probably an accompaniment of it. The rocks were locally hardened by contact action in consequence of the intrusions.

After an erosion interval, probably of comparatively short duration, the land again sank, though not so extensively nor to such depth as in the previous subsidence, and a large part of the Santa Maria district, especially the lower regions, became submerged. The deposition of the Fernando followed, beginning before the close of the Miocene. Owing to differences in altitude and possibly also to local difference in the amount of subsidence, the deposition began in some places before it did in others. Over the areas in which the Monterey has been only slightly folded, the Fernando beds assumed conformable positions with it. In regions where the Monterey beds

had been more highly tilted the later sediments were laid down unconformably. In places the first Fernando beds were of similar lithologic character to the Monterey shale, being deposited probably under similar conditions or else derived from the redeposition of the shale material. This similarity, added to the bedding conformity, caused the formations to appear as completely conformable and continuous. But the presence in places of layers of brecciated Monterey shale at the base of the Fernando, and in places of true angular unconformities, proves that a period of erosion preceded the Fernando deposition.

After the period of deposition of the finer sediments usually found at the base of the Fernando, shallow-water conditions prevailed. The deposits were almost entirely detrital, the product of erosion on land, much of the material coming from areas of Monterey shale. Fresh-water or possibly brackish-water conditions may have prevailed in the latter part of Fernando time. They certainly did for a time and locally, at least, when the brackish-water limestone beds were formed.

MAIN QUATERNARY PERIOD.

Downward and upward movements of the coastal region were probably in progress during the Fernando period, but were intensified early in Pleistocene time, and disturbance of the strata along the lines influenced by the post-Monterey upheaval took place. In this way the mountain ranges were upraised in their present position and the Fernando became warped along the lines of further folding in the Monterey.

After this uplift erosion set in and eventually removed the Fernando from some parts of the region over which it had formed a thick covering. The mountain regions were worn into rugged shapes, Santa Maria and Santa Ynez rivers developed graded valleys, and the sea planed off the coast extensively by cutting. During the same period, however, land building over this region was in progress as the result of differential movements of the coast. The great resultant changes of level in post Fernando time, as indicated by the records, were a pretty general depression to a depth of 1,100 to 1,200 feet, and locally to at least 1,400 feet; and a later uplift to the present level. These movements were probably gradual and continuous, but not sufficiently slow to allow the formation of deposits of great thickness. During these movements the sea cut into the land as the water encroached and receded, forming terraces inclined toward the ocean, and beach and shallow water sediments were laid down as thin coatings over the newly planed surfaces. These deposits were probably formed as the land rose. During the periods of depression the streams built up deposits of gravel, sand and clay at different levels, giving rise to extensive terraces and to filled valleys. Great deposits

of wind-blown sand were formed also, and their formation is continuing at present. During the late Quaternary the deposits and topographic forms resulting from all these processes have been carved by erosion; wide areas have been denuded of the thin Pleistocene capping; and in many places bits of terrace deposits are left merely as scattering remnants.

STRUCTURE AND CONDITIONS AFFECTING THE PRESENCE OF OIL.

THE ANTICLINAL THEORY.

The anticlinal theory of oil accumulation assumes that the oil, being of lesser gravity, rises above the water present in porous rocks and collects at the highest possible points in upward folds, being there confined by impervious strata arching over the folds. The presence of water, according to this theory, is considered as fundamentally necessary for the carrying out of the process of accumulation in anticlines.

The presence of oil in anticlinal folds was repeatedly observed in the eastern part of North America during the latter half of the nineteenth century. E. B. Andrews noted its occurrence along low anticlines in West Virginia and Ohio as early as 1861, and described this occurrence that same year,[a] and again, with more assurance of its wide application, in 1866.[b]

In 1863 the Canadian geologists,[c] in describing the oil springs immediately north of Lake Erie, noted their close relation to the anticlinal structure, and formulated the theory that the rise of the oil is due to the presence of water in the rocks. Their brief statement is as follows:

> Some of these springs appear to be on the line of the great anticlinal which runs through the western peninsula, and subordinate undulations of a similar character will be found connected with others. The oil, being lighter than water and permeating with it the strata, naturally runs to the highest part, which is the crown of the anticlinal, whence it escapes to the surface by some of those breaks which are usually found in such positions.

Also in 1863 Sterry Hunt, to whom the above-cited conclusions in the Canadian report are probably due, described the oil of western Ontario as derived from low anticlines.[d]

The following quotation is from an account written in 1885 by I. C. White[e] of his search for some method of determining the location of gas accumulations:

> In the prosecution of this work I was aided by a suggestion from Mr. William A. Earsenian, of Allegheny, Pa., an oil operator of many years' experience, who had

[a] Am. Jour. Sci., 2d ser., vol. 32, July, 1861, pp. 85-93.
[b] Am. Jour. Sci., 2d ser., vol. 42, July 1866, pp. 33-37.
[c] Geology of Canada, Canadian Geol. Survey, 1863, p. 379.
[d] Am. Jour. Sci., 2d ser., vol. 35, March, 1863, pp. 169-170.
[e] Science, vol. 5, No. 125, June 26, 1885.

noticed that the principal gas wells then known in western Pennsylvania were situated close to where anticlinal axes were drawn on the geological maps. From this he inferred there must be some connection between the gas wells and the anticlines. After visiting all the great gas wells that had been struck in western Pennsylvania and West Virginia, and carefully examining the geological surroundings of each, I found that every one of them was situated either directly on or near the crown of an anticlinal axis, while wells that had been bored in the syncline on either side furnished little or no gas, but in many cases large quantities of salt water. Further observation showed that the gas wells were confined to a narrow belt, only one-fourth to 1 mile wide, along the crests of the anticlinal folds. These facts seemed to connect gas territory unmistakably with the disturbance in the rocks caused by their upheaval into arches, but the crucial test was yet to be made in the actual location of good gas territory on this theory. During the last two years I have submitted it to all manner of tests, both in locating and condemning gas territory, and the general result has been to confirm the anticlinal theory beyond a reasonable doubt.

The anticlinal theory was found applicable, according to Redwood,[a] by various investigators in the Eastern Hemisphere, in the Caucasian and Carpathian fields, in India, Persia, and Algiers, and as stated by Lyman,[b] in some at least of the wells in Japan. Further credence has been lent to it by investigators in various parts of the world in subsequent reports on oil districts. It has, however, not been proved to be of universal application.

ACCUMULATION OF OIL IN THE SANTA MARIA DISTRICT.

In the Santa Maria and Lompoc fields the evidence indicates that anticlinal structure is favorable although probably not absolutely essential to the accumulation of oil. But whether or not this fact is explainable on the basis of the anticlinal theory as previously advanced, and as seemingly applicable to eastern fields, remains a question, for the reason that definite evidence is lacking regarding the presence or absence of water in the strata containing the oil. The fields of the Santa Maria district are not yet old enough to make it ascertainable whether water occupies lower levels in the same porous strata in which the oil is contained, or strata below those containing the oil, and whether water will take the place of the oil on its exhaustion in the wells; or, on the other hand, whether the oil occurs unassociated with water in large amounts. What evidence there is throws doubt on the assumption that water is present in sufficient amounts materially to affect the position of the oil in the strata. Although over a hundred wells have been sunk to depths ranging between 1,500 and considerably more than 4,000 feet in various positions relative to the axes of folds, water has been reported in only four wells at a depth of more than 1,000 feet below the surface, or below sea level, and in only a few wells below 300 or 400 feet. In other words, whatever water is present occurs in all but four wells

[a] Redwood, Boverton, assisted by Holloway, G. T.: Petroleum and its products, London, 1st ed., 1896, vol. 1, pp. 44-46; also 2d ed., 1906, vol. 1, p. 112.

[b] Geological survey of the oil lands of Japan, Tokio, 1877 and 1878.

near the surface, or at least considerably above the oil-producing zones.

It may be questioned whether the presence of water is essential for the accumulation of petroleum in the upward folds of the strata under the conditions presented by the Santa Maria and Lompoc fields. Here the oil tends to rise to the surface and form seepages wherever channels of escape are offered. This is probably not due to hydrostatic pressure, as there is no evidence that the water tended to rise in the same way; and it is just the opposite of the tendency ascribed to oil by upholders of the anticlinal theory, which would result in the oil descending and gathering in the synclinal troughs on subsidence or removal of the water. In the fields under discussion the oil is always intimately associated with gas. There do not seem to be, as a rule, separated stores of gas and oil, but the two are intermingled, or at least closely brought together, so that one is not usually found without the other, although gas is sometimes found alone. The oil exhibits a tendency to migrate, as shown by its original concentration from widely separated points of origin, by its surface seepage, and by the energetic way in which it rises in the drill holes when a source of it is tapped. This migratory faculty may be ascribed entirely to the presence of the associated gas, which would cause the oil to fill every crevice offering a point of escape or a point of lodgment. If this is granted, it is evident that the points of accumulation of oil will be determined chiefly by the presence of cavities, large or small, offering a place for it to gather. Anticlines, being points of fracturing and in some places opening out of the strata, would afford likely places for the oil to lodge in those beds subject to fracture and for it to be imprisoned by overarching impervious beds.

Aside from ideas as to accumulation of oil after such a fashion, the writers have come to the conclusion that in this region many of the "oil sands," so called, are not true sands, but zones of fractured shale or flint offering interspaces in which the oil can gather. Beds of sand in the Monterey are scarce and thin. Some of the oil-producing zones are very thick, amounting to tens or even hundreds of feet. The oil occurs chiefly in the lower portion of the formation, where brittle, flinty shale is abundant; and as it is a noticeable fact that wherever these hard, flinty layers appear at the surface they are usually much more contorted and fractured than the associated softer shales, which are, in general, only folded and not broken, it seems likely that the same fracturing and resultant formation of an ideal reservoir for the oil takes place in the depths as at the surface. Where it is so fractured, the shale occupies a greater volume than before, showing spaces some of which are open and others partially or wholly filled with chalcedonic or bituminous material. The unfractured beds are more or less impervious to the rapid migration of the petroleum, and so act as barriers to keep the oil in the porous zones.

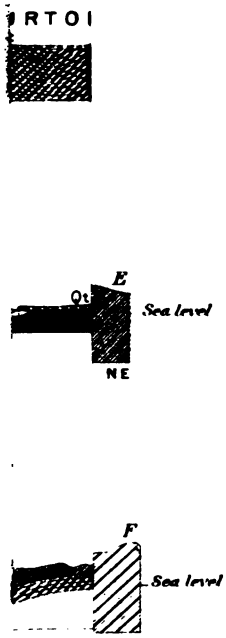
It is therefore possible that in the Santa Maria district the gas pressure is the chief agent in giving the oil mobility, and that the condition of the rocks is the chief factor that controls the matter of where the oil is stored most abundantly. Hydrostatic pressure may not play an important part. The especially large accumulations in anticlines may be accounted for primarily by the cavities offered by the strata along upward folds, and secondarily by the presence of less pervious beds arching over such folds and affording favorable conditions for the confinement of oil and gas tending to escape. Lesser stores of oil may occur at other points within the formation.

INDICATIONS OF OIL.

The chief criteria for judging as to the presence or absence of oil in appreciable quantities in this region have been the attitude of the beds, their position in the series, and the surface indications. Other minor evidences of a local nature have also been taken into account. In drawing conclusions from structural indications anticlines have been considered as the chief factors favoring accumulation, inasmuch as the oil appears to have gathered in them in a majority of the proved occurrences in this district, other conditions being favorable. The conclusion has been reached that anticlines afford a fairly trustworthy clew to the location of the most important oil deposits. Close folding appears to play a part in this district in depriving the rocks of their oil, and excessive disturbance and fracturing is unfavorable to its retention. But, on the other hand, moderate folding would appear to be favorable, if not requisite, for the accumulation of stores of oil, and probably the most favorable conditions are afforded by anticlinal folds of such sharpness as to render the brittle rocks porous by fracturing, but to leave less pervious arches of more elastic rock.

The second criterion is the statigraphic position in the formation of the beds exposed over the area in which oil is sought. As has been before stated, the oil-bearing strata occur chiefly in the lower portion of the Monterey. Where the outcropping beds belong to the higher portion of the formation there is a greater likelihood that the underlying oil-bearing strata have been able to retain their contents than where the lower strata have been denuded of the greater part of the overlying beds or where they are themselves exposed or partially removed.

As regards the third criterion, the chief surface indications are afforded by the presence of seepages of oil or tarry material from the shales, by asphalt deposits, bituminous shales, and burnt shale. Asphalt occurs mainly in three ways—as a mixture of bituminous material with sand, due to the absorption by overlying sand deposits of seepages from the shale, as hardened fillings of asphalt in cavities along joints, and as excessively saturated shale. The burnt shale is



LEGEND

SEDIMENTARY ROCKS

Recent — QUATERNARY

Alluvium

Pleistocene — QUATERNARY

Terrace deposits
(including alluvium except in larger valleys)

UNCONFORMITY

Pliocene — TERTIARY

Fernando formation

UNCONFORMITY

Miocene — TERTIARY

Monterey shale
(siliceous, bituminous, diatomaceous shales and limestone)

Tuff interbedded with the Monterey

Eocene-Miocene — TERTIARY

Vaqueros, Sespe, and Tejon formations, undifferentiated
(including some Monterey in Santa Ynez Range. Sandstone, shale, conglomerate, and limestone)

Undifferentiated — Ter.-Cret. — CRETACEOUS-TERTIARY

Pre-Monterey
(sandstone, shale, and conglomerate)

UNCONFORMITY

JURASSIC?

Franciscan formation
(chiefly serpentine intruded in sandstone, jasper, and associated metamorphic glaucophane-schist)

Asphalt

IGNEOUS ROCKS

TERTIARY?

Post-Monterey intrusives
(intrusive diabase)

PRE-TERTIARY?

Pre-Monterey intrusives
(intrusive basalt, diabase, gabbro, peridotite, and serpentine)

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the rose-colored or slaglike rock observed at many places in this and other oil-bearing regions within the Monterey formation. It is fully discussed on pages 48–52. It is the result of the burning of the hydrocarbons that have impregnated the shale, and its presence therefore indicates where seepages have existed.

GENERAL STRUCTURAL CONSIDERATIONS.

The area comprised within the limits of the Lompoc and Guadalupe quadrangles has been subjected to two systems of forces acting obliquely to each other, the one producing structural features which trend northwest and southeast, the other those which trend east and west. (See Pl. VII.) The system causing the northeast-southwest structure was probably the older and dominating one, as it brought forth the highest ranges and most extreme folding and conformed with the great system which has determined not only the Coast Ranges of California but the western border of the North American continent. The forces producing the east-west features, although exceedingly effective from the west end of the Santa Ynez Range eastward to the region south of the end of the San Joaquin Valley, were not so far-reaching as those of the other system and probably began to exert themselves at a later date.

That portion of the area under discussion which lies to the northeast of the Santa Maria Valley is dominated almost completely by structural lines trending northwest and southeast; in the extreme southern portion lines trending east and west prevail. The region between these two areas is occupied by folds and faults, some of whose component parts exhibit allegiance to one system and some to the other, but whose resultant trend is intermediate between the two. In a general way the lines of disturbance as well as the topographic relief within this central province radiate fanlike from the point of divergence of the Santa Ynez and San Rafael ranges east of the town of Santa Ynez.

The forces acting throughout the region have more often found equilibrium in the production of folds than in adjustment by faulting. Several important faults are recognizable, however, and doubtless others will be revealed by detailed work, especially in the San Rafael Range. There is evidence to show that forces have acted intermittently along the same general lines throughout a long period of time.

DETAILED DISCUSSION OF STRUCTURE.

In the field study of the structures of the formations and in the present discussion special attention has been paid to the structure of the Monterey shales, because that formation has apparently given origin to the petroleum and in it the bulk of the oil is stored.

For convenience the two quadrangles will be divided into the three naturally separated portions outlined in a preceding paragraph, viz, the region of the San Rafael Range, which includes all of the territory northeast of the Santa Maria Valley and a line extending southeast of its head; the region of the Santa Ynez Range; and the province of low hills and shallow valleys intervening between the two mountain masses. The reading of the following paragraphs describing the structure of various areas should be accompanied by reference to the map. (Pl. I, in pocket.) For the sake of compactness the conclusions as to the possibilities of productiveness of the Monterey shale have been stated, together with the description of its main structural features.

It must be remembered that in regions of great disturbance such as the shales have undergone in some parts of the area it is difficult to represent by single lines the complexity of the structure. Some of the lines, therefore, mark zones of folding rather than single definitely continuous folds. The dotted lines of structure are purely suppositional.

REGION OF THE SAN RAFAEL MOUNTAINS.

AREAS OF ROCKS OLDER THAN THE MONTEREY.

Whatever succession of beds or structural conditions may once have existed in the Franciscan formation (Jurassic?) in this district, they have been largely obliterated by the successive folding and crushing to which these rocks have been subjected in the long period of time since their first uplift. The shales and sandstones mapped as pre-Monterey, especially where the beds alternate, have preserved the folds well, but except on North Fork of Labrea Creek and along Sisquoc River no effort has been made to work out the structure of this series.

AREAS OF MONTEREY AND LATER FORMATIONS.

FOLDS.

Considered as a whole the Monterey has been thrown into a series of anticlinal and synclinal folds striking about N. 50° W., and apparently plunging, in the main, toward the northwest. Great variation exists in the relative steepness of dip along these folds, but it is evident that the compressive forces producing them were of much greater strength in the southeastern part of the area, between Bone Mountain and Round Corral Canyon and thence southeastward into the region of Zaca Peak. Here the folds become so compressed and in places overturned that it is difficult to trace them. Pl. III, *B* (p. 34) and VI, *B* (p. 46) give an idea of the closeness of the folding. In contrast with this constricted portion is the broad series of folds which extend

rather uniformly along the northeastern border of the area, and develop toward the southeast into the syncline crossing Tunnel Canyon and Horse Gulch just north of Sisquoc River. The high, broad ridge between Bone Mountain and Manzanita Mountain is composed of Monterey shale, which lies approximately flat, and toward the northwest becomes one arm of the great syncline which extends through Goodchild's ranch on Labrea Creek and is traceable almost to Colson Fork of Tepusquet Creek. A similar syncline, possibly the same, extends from Colson Fork northwestward across Tepusquet Creek to the margin of the Lompoc quadrangle. The northeastern arm of this fold forms the high ridge extending along the southwestern side of Buckhorn Canyon.

It is possible that the pre-Monterey rocks north of Bee Rock Canyon plunge down monoclinally under the Vaqueros in a fold at right angles to the wide anticlinal fold that exposes the former. Such a plunge would be apt to give rise to the northeast-southwest table between Bone Mountain and Manzanita Mountain that interrupts the structure to the northwest and southeast, and this table may, therefore, represent a buckling across an otherwise continuous structure.

Southwest of Los Coches Mountain one or more folds are overturned, but the northwestern extensions of these folds have not been examined.

The region southeast of Round Corral and Asphaltum creeks is occupied by several sharp folds which strike in a general northwest-southeast direction. Overturning is not uncommon in this series of folds, one notable example being an anticline on the southern flank of Zaca Peak. West of Round Corral Creek the structure lines bow around from a northwesterly to a westerly or west-southwesterly direction, the folds at the same time becoming less compressed and the conditions for the retention of the oil in the basal sands of the hard shale series correspondingly better.

FAULTS.

There is strong evidence of a fault zone passing north of the narrow area of intrusive rock north of Zaca Lake, and thence northwestward as far as the head of Rattlesnake Canyon. The resultant downthrow along this zone of displacement is on the southwest, probably amounting to a good many hundred feet toward the east edge of the Lompoc quadrangle. Toward the northwest this fault apparently dies out or merges into a syncline.

Just east of Los Coches Mountain there may be another fault which brings up the uppermost Vaqueros on the north. A third fault between the Pliocene and Monterey may extend from a point near the mouth of Round Corral Canyon to Labrea Creek.

Faults also occur along the Franciscan-Fernando contact in the region northwest and southeast of Figueroa Creek, but the resultant throw was not determined. A depositional contact is clearly exposed along this same line just northwest of Alamo Pintado Creek.

EVIDENCES OF PETROLEUM.

Despite the great development of folds within the Monterey area, only here and there do seepages of asphaltic material occur. It would seem that the fractures produced by sharp folding would give adequate channels for the escape of petroleum, and it is surprising to find so few seepages. The best developed of these is on Labrea Creek at and near its junction with Rattlesnake Canyon, and is typical of the localities noted north of Sisquoc River. The oil seepage is associated with small springs of strongly saline and sulphurous water, and the oil has exuded along the bedding planes of the Monterey shales, here thrown into a pronounced anticline which has been flexed in such a manner as to open out the laminæ of the shale and thus give better opportunity for the passage of oil. Two wells have been sunk here, but they are shallow and offer no additional data.

The following is a brief statement of the asphalt seepages and brea deposits occurring in the San Rafael Mountains:

1. Branch of upper Tepusquet Creek. Slight seepage in bed of creek three-fourths of a mile above junction with main stream. At anticlinal axis. Has been located.
2. On Colson Fork of Tepusquet Creek. Black bituminous streaks, veinlets, and pockets, associated with calcareous shales which are considerably folded on a minor scale. This also has been located.
3. Labrea Creek, at and near junction with Rattlesnake Canyon.
4. Sisquoc dairy. Seepage and asphaltic sands along sharply defined anticline which is obscured by later material. Well sunk here, but no record available.
5. Sisquoc River, one-half mile below Round Corral Canyon. Slight seepage from steeply inclined Monterey shale. (Shown in Pl. III, *B*, p. 34.)
6. Fugler Point, 1 mile north of Gary. Veins of asphaltum, parallel in a general way to the bedding, which here dips 25° SW., intrude the fossiliferous Fernando (lower Pliocene portion). A shaft has been sunk here a few feet for the removal of the asphaltum.
7. Alcatraz mine, 3½ miles east of Sisquoc post-office. Vast deposits of asphaltum, from a few feet to 200 feet or more in thickness, lie unconformably above the steeply dipping Monterey shales over large areas in the general region of the mine. These deposits have been mined on a large scale at one place, but at present the plant is idle. The mine is shown in Pl. VIII, *A*.
8. Zaca Canyon, 5 miles southeast of Sisquoc post-office. Deposits similar to those at the Alcatraz mine are found on both sides of La Zaca Creek where it debouches from its narrow mountain canyon into the broad valley carved by it through the hilly country.
9. Sisquoc Ridge, 1¾ miles north of Sisquoc post-office. A small but significant area similar in occurrence to the two preceding. This area overlies the axis of an anticline in the Monterey shale.

A. ALCATRAZ ASPHALT MINE, 3 MILES EAST OF SISQUOC.

Showing the horizontal Fernando brea deposits overlying the steeply tilted Monterey shale.

B. UNCONFORMITY BETWEEN TILTED MONTEREY SHALE AND HORIZONTAL PLEISTOCENE SAND AND GRAVEL.

In railroad cut northeast of Casmalia. Photograph by Ralph Arnold.

CONCLUSIONS REGARDING FUTURE DEVELOPMENT.

On account of the greater intensity of the folding and the lack of the thick, more or less unaltered diatomaceous deposits which are found associated with all the proved productive fields in this district, the indications are not so encouraging for good wells in the territory northeast of the head of the Santa Maria Valley as they are in certain other portions of the Lompoc and Guadalupe quadrangles. The areas in the region of the San Rafael Mountains which offer the most inducements for testing by the drill are as follows:

1. North and northwest of Sisquoc post-office, along the anticlines shown on the map (Pl. I, in pocket). There are one or two local anticlines not shown, which might also be prospected with good results. The hard shales exposed in this region are probably lower Monterey and, if such, do not offer as much promise of great accumulations of oil at their base as if they were overlain by the upper part of the formation. The strata in the region above the headwaters of Round Corral Canyon and Asphaltum Creek are too sharply folded to give much hope of the retention of large deposits of petroleum. The asphaltum deposits here and to the southeast indicate that the Miocene was at one time highly petroliferous, but that at least a considerable portion of the oil has escaped.

2. In the Monterey area bordering the head of the Santa Maria Valley on the northeast, both west and east of Tepusquet Creek, wherever the anticlines are not so sharply folded as to give indications of probable loss of their petroleum content by excessive fracturing. The surface evidence of petroleum in this general Monterey area is greatest in the southeastern or more sharply folded portion, but for obvious reasons it seems likely that the chances for the accumulation of economically important deposits of petroleum are greatest in the less compressed area northwest of Labrea Creek.

3. The region about Fugler Point and thence southward and southeastward toward Sisquoc. This territory is doubtless underlain by the oil-bearing beds, but at what depth it is not possible to calculate owing to the fact that the Monterey and Fernando are covered by later sediments. The occurrence of asphaltum at Fugler Point is analogous to that at the east end of Graciosa Ridge, near which very productive territory has been developed. The local dip at the point (25° SW.) would indicate that the best places to drill would be east of the asphaltum deposit; but the uncertainty whether this dip is anything more than a local tilting of the Fernando is so great that conclusions regarding the best localities for exploitation in this immediate vicinity are extremely hazardous. Southwest of Fugler Point, however, there is evidence of the presence of a low

anticline which should yield good returns if penetrated deep enough. This anticline is mentioned further in connection with the Canada del Gato[a] area (pp. 88–89).

REGION OF SANTA YNEZ MOUNTAINS.

AREA SOUTH OF LOMPOC.

South of the Lompoc Valley, the Monterey dips in general northward away from the higher portion of the hills, but south of the town of Lompoc is an area of much disturbance, and many folds have been developed on the flank of what may be thus broadly considered as a monocline. These folds have been compressed in different directions and there is a puzzling diversity of dip and strike. There are so many local folds that it is difficult to connect the more important axes, but the general lines of disturbance are continuous for the distance mapped. The main folds south of Lompoc are an anticline near the valley and a syncline north of the Monterey-Vaqueros contact, with a minor anticline and syncline between. The attitude of the beds is extremely variable, the dip ranging in general between 15° and 60°. On either side of the main anticline between Salsipuedes and San Miguelito creeks the hard shales dip away at an angle of 20° to 40°. West of San Miguelito Creek the folds swing out toward the valley or die out on the flank of the monocline, which thus becomes unbroken.

The greater part of the strata in the hills south of Lompoc belong low in the Monterey formation, although higher portions remain in the synclinal folds. The disturbance has been considerable, and erosion has removed the highest parts of the formation, so that the chances have been good for the escape of any oil that may have been present. There are no surface indications of petroleum and the conclusion is that no great quantity of oil would be found on drilling.

AREA OF SANTA RITA HILLS.

East of Lompoc the lines of structure cross the Santa Ynez Valley into the Santa Rita Hills. These hills are formed of a single main ridge which is paralleled on the south side by an important anticline. The dips on either side of the broad summit of this fold range from a few degrees to about 35°. The general trend of the fold is east and west, in conformity with that of the Santa Ynez Range, but it is curved, especially at the east end, as if influenced by more than one set of forces. Other important folds occur on the flanks of the anticline, giving origin to the disturbed zone followed by Santa Ynez River.

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[a] Called locally Cat Canyon.

A, B. MONOCLINE IN MONT

About 1½ miles northwest of Casmalia, lo

C, D. GRACIOSA AND WESTER

South side of Santa Maria field; Mount So

Y SHALE IN CASMALIA HILLS.

northwest. Photograph by Ralph Arnold.

NION OIL COMPANIES' WELLS.

In distance. Photograph by Ralph Arnold.

The conditions along this anticline, especially through the eastern half of its length, favor the occurrence of some oil at least, as the axis exposes beds fairly high in the formation and the folding is gentle. No surface indications of petroleum were found, except a patch of burnt shale south of the road about 1 mile southwest of the highest hill (elevation 1,300 feet) and local outcrops of bituminous black flint and brown shale on the west side of the 800-foot hill about half a mile north of the river and 1½ miles west of the east edge of the Santa Rosa grant.

MAIN PORTION OF THE SANTA YNEZ RANGE.

The Santa Ynez Range is composed chiefly of Tejon and Vaqueros rocks and its structure is therefore much less important in connection with the oil deposits than that of the areas underlain by the Monterey shale. It is dominated by a great southward-dipping monocline that forms a high ridge along the coast, north of which the strata are gently folded along curving lines that reflect two different structural trends. The folds that expose the Tejon-Vaqueros and the underlying Franciscan beneath the Monterey toward the west end of the range are in places abrupt and complex. The anticline of the Santa Rita Hills has the appearance of crossing the Santa Ynez Valley and continuing in a large fold to the southeast.

REGION BETWEEN THE SAN RAFAEL AND SANTA YNEZ MOUNTAINS.

CASMALIA HILLS AND SAN ANTONIO TERRACE.

Two dominant structural lines control the region of the Casmalia Hills and the San Antonio terrace. One is a typical fault starting on the coast south of Lions Head and the long area of igneous rocks and running southeastward. About 2 miles west of Casmalia the line is continued by an anticline, which is probably affected by faults at least as far as Schumann Canyon. This anticline plunges more and more toward the southeast and loses its character as a fold, giving place to the eastward-dipping monocline of the San Antonio terrace.

The other structure line is one of varying character, represented on the map as the Schumann anticline. Northeast of the area of igneous rocks that meets the sea at Lions Head Miocene strata form a great monocline, dipping rather steeply to the northeast. In the high region of Mount Lospe and northeast of the long strike ridges (shown in Pl. IX, *A*, *B*) that extend southeastward from that peak, this monocline flattens out into a structural platform of very low dip, which on approaching the edge of the steep descent to the Santa Maria Valley bends over and drops off abruptly. The axis along which this steepening of the dip occurs is in a way equivalent

to an anticlinal axis and is the line mapped. In places it is a true anticline, completed by beds of gentle dip that form a broad syncline of the platform on its southwest side. South of Corralillos Creek the structure curves westward and the Schumann anticline is sharply defined and overturned. It is seemingly to be correlated with a large anticline exposed in the Tejon-Vaqueros rocks on the coast north of Point Sal. South of Waldorf this anticline, as shown by the dotted line on the map, is not certainly continuous, but west and south of Schumann the same or a similar fold becomes well developed and the strata dip away from it on both sides. In this portion and southeast of Schumann Canyon its summit is broad, but the dips become very steep farther out on its northeastern flank. It plunges to the southeast and finally dies out.

Asphalt and other surface indications of oil, such as burnt shale and bituminous shale, occur at many places in the Casmalia Hills. The shale is especially bituminous along and near its contact with the Fernando on the northeastern side of that part of the hills which lies north of Schumann, and it has been burnt in a number of places in the same region. Outcrops of burnt shale are prominent on the hill just southeast of Schumann, and near the contact at the northern base of this hill the shale is extremely bituminous. Wells put down in the region about Schumann encounter heavy tar at depths below 2,000 feet, but no paying wells have been struck. It seems likely, however, that at greater depths, possibly 3,000 feet or so, the horizon of the productive flinty beds encountered in the Graciosa Ridge wells will be penetrated and will yield lighter oil in paying quantities.

The region lying north of Schumann Canyon, west of the valley that runs southward out of the hills and opens to Schumann Canyon 1 mile N. 45° W. of the Casmalia depot, and west of the road that crosses the ridge to Waldorf will probably not yield any large quantity of petroleum, because the strata are so low in the formation and because there appear to be no sufficiently well-developed folds to afford good points of accumulation. Oil might be found in small quantities in the minor folds between the lower portion of Schumann Canyon and the fault. The shale along the coast here is very bituminous. East and south of the supposedly unproductive region outlined above the plunging structure exposes higher portions of the Monterey shale and the conditions warrant the conclusion that oil can probably be obtained in the neighborhood of the major anticline. Southeast of the point where the road south of Waldorf crosses the ridge the territory appears promising, especially along the anticline and on its east side. The oil which is supposed to rise on the steep eastern flank of the fold probably does not reach far under the broad western flank. South of Schumann, where the fold

becomes more nearly normal, both flanks will probably be found productive if penetrated deep enough. The surface structure indicates that the oil horizon plunges to a greater and greater depth under the whole region southeast of Casmalia Creek. The anticline south of Antonio is well defined and conditions favor the presence of oil on both this and the other anticline of the San Antonio terrace.

The main anticline on the coast north of Point Sal, already mentioned, is in the Vaqueros and is doubtless barren of oil. North of this locality the Monterey is decidedly bituminous, but no special circumstances point to the existence of petroleum in large quantity. It is quite possible that the region north of Mussel Rock, the next point to the north, would prove promising if the surface covering allowed the examination of the underlying formations and the determination of anticlines. The structure seems to cause the formations to plunge toward the north from the north end of the Casmalia Hills, and a fairly high portion of the Monterey may underlie the region at the mouth of the Santa Maria Valley.

BURTON MESA.

The plateau known as Burton Mesa is a region of numerous low folds in the Monterey. Along the coast the flinty shales are of low dip, but folded and contorted in a complex way. The folds indicated on the map are the most important ones, but whether or not they are perfectly continuous units across the mesa can not be definitely ascertained on account of the covering of sand over the shale. The mesa appears to be structurally a continuation of the region near Lompoc as much as it is of the Purisima Hills, although topographically it is a continuation of the latter. In the neighborhood of Pine and Santa Lucia canyons there is a thick series of shales striking far to the north of west and directing the structural lines across the Lompoc Valley as if to join those in that region that show a tendency to curve northward. West of Pine Canyon the strike changes. The Pine Canyon anticline shows this curving structure. It is a well-defined fold with broad summits and supports on its flanks a considerable thickness of shale. The dip ranges from 10° to 30°. A characteristic appearance of the shale and dip on the northeastern flank is shown in Pl. IV, *B* (p. 36). North of this fold occur a number of minor flexures and there is some doubt as to the continuity of the anticline mapped at the head of Oak Canyon with the well-defined fold near the coast in the vicinity of Canada Tortuga. A well-marked low anticline occurs near the coast north of Lompoc Landing and probably continues inland. It is probable that either one anticline of considerable importance or several small component flexures start across the mesa between Tangair and San Antonio Creek. The summit of all these anticlines so far

mentioned on Burton Mesa exposes hard shale that is low down in the Monterey, and it is probable that with the removal of all of the higher portion opportunity has been offered for the escape of the greater part of the oil from the basal beds.

A low anticlinal fold occurs in the northeast corner of Burton Mesa and plunges toward the southeast. As indicated by the dotted line on the map, it is possibly a continuation of the anticline south of Antonio before mentioned and another on the east edge of the mesa that is discussed in connection with the Purisima Hills. The evidence of folds in this northeastern portion of the mesa is scanty, but it is probable that where they occur accumulations of oil are present.

The brittle calcareous and flinty shale of the lower portion of the Monterey that is exposed along the coast edge of Burton Mesa is very bituminous. The petroleum slowly oozes out in some places and collects in tarry patches over the shale. Up Oak Canyon the shale is bituminous, pockets of tar being found in places in the flint on the surface. On the northern border of the mesa, near the point where the road to Lompoc comes up the grade, a 3-inch bed of bituminous sand was found traversing the shale fairly high in the formation.

PURISIMA HILLS.

FOLDS.

The Purisima Hills are formed by one broad anticline which has its axis on the south side of the summit of the dominating ridge. Through the major portion of this anticline's course, from the region north of the Hill wells to a point beyond Redrock Mountain, the beds lie almost horizontal on its summit, becoming gradually steeper up to an angle of 15° or 20°, or locally even 40°, within a mile or two from the axis. The general trend of this fold is more to the north of west than that of the Los Alamos or Santa Ynez valleys, but portions of it have a more westerly course, as at the west end, where it also becomes a steeper fold. At the east end it has the dominant northwest-southeast trend characteristic of this part of the hills and likewise becomes steeper. It is a fold plunging from either end toward the region at the head of Cebada Canyon, where the axis of the depression in the anticline occurs. This depression appears like a broad syncline crossing the anticline at right angles, with the deepest portion of its trough at this point.

The Purisima Hills anticline can not be traced farther westward than is shown on the map, but at the west end there seems to occur a structural offset to the northwest, a poorly exposed anticline about a mile from the end of the main fold being traceable for a short distance and seeming to mark the continuation of the general structure of these hills. There is a likelihood that oil may be found along this fold as well as along the main anticline.

FAULTS AND ASPHALT DEPOSITS.

A thrust fault is well exposed in two forks of Cebada Canyon, where the Monterey has been thrust to the southwest up over the Fernando. The dip of the fault plane is toward the northeast at an angle of about 30°. The movement has amounted to a few hundred feet. The fault zone seems to continue for a considerable distance toward the northwest and to be marked near the Wise & Denigan oil well No. 8 by large asphalt deposits occupying fractures in the Fernando that dip at an angle corresponding to that of the fault plane. The asphalt back of the Wise & Denigan well No. 1 is probably due to oil that has seeped through the same fractured zone and collected in the sandy capping.

The structure of these hills is further complicated by a prominent overturned anticline in the Monterey along the contact with the Fernando southwest of Los Alamos and by what appears to be a fault exposed near the mouth of Canada Laguna Seca. In this fault the Fernando limestone and sand are thrown down several hundred feet on the north, at the edge of the Los Alamos Valley.

In addition to the deposits above noted, asphalt occurs in great abundance south and east of Redrock Mountain, surrounded by a large area of very bituminous shale and burnt shale. Undoubtedly an immense amount of petroleum has escaped here, but it is not probable that the supply is exhausted. On the contrary, the presence of this petroliferous material on the surface, coupled with the favorable structural conditions, points strongly to the existence of rich oil deposits beneath.

A large mass of asphalt is present in the much-fractured Monterey shale west of La Zaca Creek, and very bituminous shale approaching asphalt in character occurs on the creek south of Zaca station. The shale is bituminous throughout the zone of disturbance traversed by this creek south of Zaca. On account of the low position of the strata in the formation and the severe fracturing and folding that have taken place, it seems probable that the conditions have been favorable in this eastern portion of the Purisima Hills for the escape of much of the petroleum.

Small beds of bituminous sands interbedded with soft shale occur in the upper portion of the Monterey just east of Canada de la Puenta, about three-fourths of a mile south of the Los Alamos Valley; also on the north side of the Purisima Hills ridge, about 2 miles south of Harris. A small patch of shale that is saturated with bituminous material is exposed in the canyon followed by the road 1 mile south of the Los Alamos Oil and Development Company well No. 1, and the shale is bituminous in the neighborhood of the Todos Santos well.

CONCLUSIONS REGARDING FUTURE DEVELOPMENT.

The Purisima Hills anticlinal fold seems to offer a favorable location for oil wells along most of its south flank. Owing to the plunging of the fold toward its middle, lower and lower strata are reached as its extremities are approached. In the region mapped as Fernando, between the Hill wells and the head of Canada Laguna Seca, the summit beds of the Monterey are overlain by later sand and a well would have to be drilled to a great depth before reaching the oil horizon. East and west of that region the oil horizon probably approaches nearer to the surface. In the vicinity of Redrock Mountain, especially to the west of it, the conditions seem very favorable for the occurrence of oil. Farther east, near La Zaca Creek, a much lower portion of the Monterey is exposed and the rocks have been affected by considerable disturbance, so that it is less likely that large accumulations of oil will be found there.

AREA AROUND SANTA YNEZ.

The Santa Ynez anticline is a distinct steep fold exposed southeast of the town of that name. It supports on its flanks a thickness of at least 2,500 feet of calcareous and porcelaneous shales belonging to the lower portion of the Monterey. The dips at the axis range between 50° and 80°, but become lower toward either side. This fold is seemingly a structural continuation of that of the Purisima Hills, and it probably extends under the gravels of the region around Santa Ynez, its axis passing approximately under that town. But it is doubtful whether it is actually the same as either of the anticlines that are shown on the map as stopping indefinitely near the east end of the Purisima Hills. The terraced stretch between La Zaca Creek and Ballard seems from the fragmentary evidence obtainable to be in a way an undulating structural plateau formed of beds low in the oil-bearing shale, dipping at slight angles in various directions. It is probable that the structure of the Purisima Hills is here interrupted, but continued in a general way beyond by the Santa Ynez anticline. Owing to the low position of the beds in the formation, the chances for finding a considerable amount of oil along this anticline do not seem to be as good as farther west. No surface evidence of petroleum was seen. Any definite statements, however, in regard to the region between Los Olivos and Santa Ynez River and between La Zaca Creek and the east edge of the area mapped are hazardous, for the reason that the widespread terrace deposits obscure practically all of the structure.

SOLOMON HILLS AND AREA NORTH OF LOS OLIVOS.

GENERAL FEATURES.

Three anticlines dominate the structure of the Solomon Hills. These are, in order from west to east, the Mount Solomon anticline (first worked out and named by W. W. Orcutt), the Gato Ridge anticline, and the La Zaca Creek–Lisque Creek anticline. In addition to these there are at least three or four minor anticlines associated with the first named, and at least one north of that on Gato Ridge.

MOUNT SOLOMON AND ASSOCIATED ANTICLINES.

Structure.—The details of the northwest end of the Mount Solomon and associated anticlines are shown on the contour map (Pl. X, p. 92). Whether or not the anticline extending through the Santa Maria Oil and Gas and the Escolle properties should be considered the true extension of the Mount Solomon anticline, or whether the Hartnell anticline should be so considered, is impossible to decide with the data at present available. It is the writers' opinion that the Mount Solomon and Hartnell anticlines are the result of the same set of forces and should therefore be considered as one fold, but that the evidence offered by the data used in compiling the map favored the relations shown on Pl. X. The mapping of the Pinal, Hobbs, and Newlove anticlines is based almost entirely on evidence furnished by the drill, although certain superficial evidence strengthens the theory of their presence.

The southeastern portion of the Mount Solomon anticline gradually fades out into the southern flank of the Gato Ridge anticline, losing its individuality toward the southeast end of the Mount Solomon ridge. The northeastern flank of the anticline is much the steeper, dipping from 20° to 38° in the region of Mount Solomon, and gradually flattening out from that locality southeastward.

The Western Union anticline is a well-developed flexure with steep northern flank just south of the eastern group of Western Union wells, but its identity becomes more and more obscure as it fades into the southwestern flank of the Gato Ridge anticline in a similar manner to the Mount Solomon anticline, just south of the latter's southeast end.

The relations existing between the Mount Solomon and Schumann anticlines are vague, although it is certain that they are not in alignment and therefore can not possibly be one continuous feature. If the Hartnell and Mount Solomon anticlines are considered as one, the relations which exist between this united anticline and the Schumann anticline are exactly analogous to those which exist between the Mount Solomon and Gato Ridge and the Gato Ridge and La

Zaca Creek-Lisque Creek anticlines, viz, the adjacent anticlines are en échelon with each other, each plunging down past the end of its neighbor. Graciosa and Harris canyons, particularly the former, are the superficial reflection of the syncline between the ends of the Mount Solomon and Schumann anticlines, and Solomon Canyon and Canada de los Alisos occupy analogous positions between the Mount Solomon and Gato Ridge and the Gato Ridge and La Zaca Creek-Lisque Creek anticlines, respectively.

Asphaltum deposits.—Practically the whole top of Graciosa Ridge is capped by post-Monterey sandstones and conglomerates, which are heavily charged with asphaltum. Asphaltum also occurs as veins penetrating the Monterey and post-Monterey beds at the east end of the ridge, and a fine example of asphaltum veins and veinlets filling the joint cracks in the Monterey is to be seen beside the road leading up to the Santa Maria Oil and Gas (Squires) well No. 4. This occurrence of the asphaltum in the joint cracks of the shale gives a clew to the probable channels through which the oil migrated from the depths to the surface, and leads to the general conclusion that joint cracks are the reservoirs and channels of migration of the oil in many of the productive strata of this field.

Conclusions regarding future development.—It is obvious from a glance at the contour map (Pl. X, p. 92) and a perusal of the detailed description of the developed areas that practically all of the territory covered by contour lines is productive. The only part of the region about which the compiler of the map has any misgivings as to productiveness is that occupying a general synclinal position south of the great bend in the Mount Solomon anticline. These misgivings are partially alleviated, however, by the idea that probably the position of the territory in question on the flanks of Graciosa Ridge, which is, broadly, a quaquaversal fold or dome, may exert enough control on the oil to cause its collection there at least in paying quantities, if not in the remarkable measure found in other parts of this field. The region adjacent to the southeast end of the axis of the Mount Solomon anticline ought to be productive. The beds on the northeastern flank dip more steeply than those on the southwestern, and the first productive stratum is thought to be at a lower horizon in the shale on the former flank than on the latter, so that it is probable that the oil zone will be struck at a greater depth from the surface northeast of the anticline than southwest of it.

GATO RIDGE ANTICLINE.

Structure.—The Gato Ridge anticline extends from the top of the ridge just east of the mouth of Solomon Canyon to a point somewhere near the middle of the triangle formed by Canada de los Alisos, Cuaslui Creek. and Foxen Canyon. It follows very closely

the crest of the ridge between Canada del Gato and Solomon Canyon and for a considerable distance to the east is coincident with the highest topographic features. In general, the anticline plunges from the southeast toward the northwest, the lowest beds along its axis being exposed in the region of Canada Arena. The Fernando is the only formation exposed along the entire length of the anticline. With the exception of some diatomaceous beds which closely resemble and were at first mistaken for Monterey shale, the rocks exposed are sandstone and conglomerate.

The northwestern portion of the fold, from the Howard Canyon road northwestward, is a gentle arch with dips on the flanks rarely more than 5°, except northwest of Los Alamos, where the dips of some of the youngest beds exposed change abruptly from 3° or 4° to 15°. The northwestern extremity of the anticline fades off into the low slopes toward the Santa Maria Valley. From Howard Canyon eastward the southerly dip increases rapidly in steepness until in the region of Canada de los Coches it attains a slope of 25° to 35°, the steepest dip being at the junction of the canyon last named and Canada Arena. Although the southerly dip increases in steepness toward the east along the anticline, the dip of the northern slope becomes less, ranging from 12° or 15° in the region of Howard Canyon to 3° or 4° just west of Canada Arena, and finally changing to a gentle southward slope in the region of Cuaslui Creek, thus fading into the southern flank of one of the folds emanating from the region at the head of Round Corral Canyon and Asphaltum Creek. In the region of Cuaslui Creek the flexure is therefore not a typical anticline in the regularly accepted sense, the horizontal being used as datum, but in every other way it conforms to the characters of such a structural feature.

On the ridge north of the central portion of Canada del Gato and extending indefinitely northwestward out into the Santa Maria Valley a mile or so southwest of Gary is a low anticline, the southeastern end of which merges into the almost horizontal northern flank of the Gato Ridge anticline. At no place along its course is this structural feature well developed, although it appears to be fairly persistent for a considerable distance.

Evidences of petroleum.—Very little surface evidence of the existence of petroleum in the Gato Ridge anticline is to be had along its course. Near its axis in Cuaslui Creek and north of the head of Howard Canyon, however, the Fernando shale is slightly bituminous. The Pezzoni well, in Canada Arena; the Williams well, near Canada del Gato, 1½ miles west of the Howard Canyon road, and the Palmer Oil Company's well No. 1, 1 mile west of the lower part of Canada del Gato, all approximately a mile north of the anticline, offer indisputable evidence of the presence of the oil-bearing rocks

along a considerable extent of its northern flank. In the region of the Pezzoni well an unproductive oil and gas bed is encountered at about 1,200 feet below the surface, immediately followed by a diabase or lava rock in which the ferromagnesian minerals have been weathered to serpentine. In the Williams well the same or a similar oil and gas bed occurs much lower. The well was abandoned owing to the terrific gas pressure, which heaved heavy tar up into the hole and stopped operations. The Palmer well is productive, yielding oil of 16° or 17° gravity. Although not directly associated with the minor anticline northeast of Canada del Gato, the asphaltum occurring at Fugler Point, 1 mile north of Gary, is important in indicating the probable presence of petroleum in the upper end of the Santa Maria Valley.

Conclusions regarding future development.—The region north of the Gato Ridge anticline, from the vicinity of Cuaslui Creek westward to a point at least a mile beyond the Howard Canyon road, is underlain by strata so nearly horizontal as to preclude their containing very productive accumulations of petroleum. North and northwest of this region, however, especially near the axes of the Gato Ridge anticline and the anticline north of it, the indications are good for productive wells. The conditions for the accumulation of petroleum are also good along and just south of the axis of the Gato Ridge anticline in the vicinity of Cuaslui Creek and from this locality westward to the upper portion of Canada de los Coches. The same might be said of the immediate vicinity of the row of prominent knobs which extend in a straight line northwestward for 5 miles from a point about a mile north of Los Alamos, and possibly also, but in a less degree, for the territory between these knobs and the axis of the anticline. These knobs mark an abrupt change in the dip of the beds from 3° to 12° SW. to 35° or 40° or possibly more, in the same direction. Wells would have to be sunk to a considerable depth along this last-mentioned line to reach the oil horizons, but if oil was encountered at all it would probably be in such quantities as to pay for the deep holes.

LA ZACA CREEK–LISQUE CREEK ANTICLINE.

Structure.—The La Zaca Creek–Lisque Creek anticline extends from the ridge southeast of Canada del Comasa southeastward at least as far as the edge of the Lompoc quadrangle east of Santa Agueda Creek. Its course is practically straight except at the northwestern extremity, which bows around toward the southwest and is en échelon with the east end of the Gato Ridge anticline. The dips along the axis are low in both directions, but distant from it they are much steeper, being as high as 30° or more to the northeast on the second

ridge east of Figueroa Creek, as shown in Pl. VI, *A* (p. 46), and 30° SW. at the junction of Figueroa and Lisque creeks.

Conclusions regarding future development.—No indications of petroleum were noticed in proximity to this anticline, and it is almost certain that no productive wells will be developed on that part of it which lies within the Lompoc quadrangle, with the possible exception of a small area at its west end. There are good reasons for believing that the oil-bearing beds are absent from most of its northern flank, and if present under certain portions of its southern flank they lie at such a depth as to preclude their successful exploitation.

SUMMARY OF CONCLUSIONS REGARDING FUTURE DEVELOPMENT.

There can be no doubt that the region treated in this report is one of great promise. The structural and other conditions in general favor not only much more extensive development of the territory that has already been tested, but also the development of new fields. It must be borne in mind continually, however, that absolute determination, by work on the surface, of the possibilities of occurrence or nonoccurrence of oil in any one locality is not possible. The best that can be done is to calculate the degree of probability on the basis of a summation of surface indications and structural conditions.

The following is a list of the tracts that appear especially to invite testing with the drill. Most of them have been discussed in the foregoing pages:

North and northeast of Sisquoc post-office, along anticlines.

General region east and west of Tepusquet Creek.

Indefinite area west of Gary, about Fugler Point.

Santa Rita Hills anticline.

Near the coast north of Schumann Canyon.

Schumann anticline in southeastern part of Casmalia Hills.

Two anticlines on San Antonio terrace.

Questionable region at mouth of Santa Maria Valley.

Northeastern portion of Burton Mesa.

Purisima Hills anticline, more especially the south side.

Anticline at head of Santa Lucia Canyon.

Region about Mount Solomon and related anticlines.

Along Gato Ridge anticline and south of it between Canada de los Alisos and Canada de los Coches.

Row of knobs extending 5 miles northwestward from a point about 1 mile north of Los Alamos and the territory between these knobs and the Gato Ridge anticline.

Region northwest of the head of Howard Canyon, especially along the axis of the anticline south of Gary.

Arroyo Grande field. (See pp. 107–108.)

DETAILS OF THE DEVELOPED TERRITORY.

DEFINITION OF FIELDS.

In the following paragraphs are discussed the more imp details regarding the structure, geology, oil zones, oil, and prod in the areas in which development is well under way. These within the Lompoc and Guadalupe quadrangles fall naturall two fields—the Santa Maria field and the Lompoc field. The f covers the whole territory between the Los Alamos and Santa valleys, and the latter is used to designate the region south of tl Alamos Valley. A third, the Arroyo Grande field, covering tl ritory north and northwest of the town of that name in Sa Obispo County, lies to the north of the region mapped, but is discussed. A note on the Huasna field, east of Arroyo Gra also appended.

SANTA MARIA FIELD.

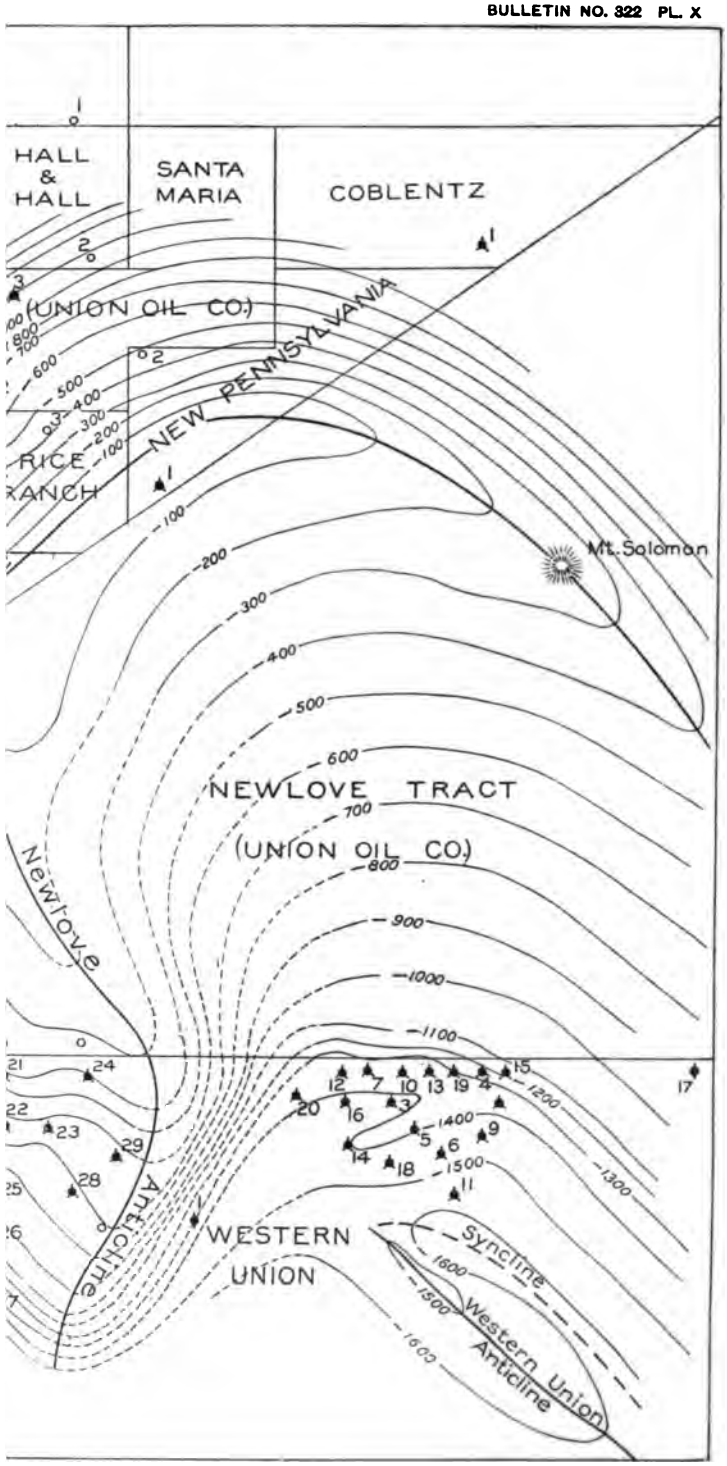
CONTOUR MAP.

WHAT IT SHOWS.

The contour map of the Santa Maria field (Pl. X) shows the b aries of the different properties, the approximate location of wells, and the general structure of the field. The structure i cated by contours showing the distance below sea level of a thetical horizon, zone, or bed, which just reaches sea level highest part of the axis of the Mount Solomon anticline. Th tour interval is 100 feet. By means of this map the directic amount of dip of the strata in the oil-bearing Monterey shale n calculated for any point in the field, as the contour lines sh direction of strike (to which the dip is at right angles), and th zontal distance between any two contours is the distance tl which the beds dip 100 feet at that particular point.

BASIS OF CONTOUR MAP.

The property lines were sketched from a map kindly furnis Frank M. Anderson. The wells were located in the field by tl supplemented by pacing and in some instances by informatic nished by the managers of properties. The log of every well area either finished or down any considerable distance in A 1906, was used in the determination of the structure and the pilation of the data concerning the oil zones. All additional in tion available up to January 15, 1907, has been used in a revi the contouring. All of the obtainable surface evidence of di strike of the beds was also used in the preparation of the ma every case where the surface and well-log evidence were at va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COBLENTZ
(UNION OIL CO.)
NEW PENNSYLVANIA
RICE RANCH
Mt. Solomon
NEWLOVE TRACT
(UNION OIL CO.)
Newlove Anticline
WESTERN UNION
Syncline
Western Union Anticline

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the latter was followed. In the Fernando formation, which unconformably overlies the Monterey shale, it was natural to expect variance with the structure in the Monterey, but even here the surface evidence more often supported than contradicted the evidence obtained by the drill.

DIFFICULTIES OF PREPARATION.

After carefully plotting all the logs on a uniform scale it was found that the greatest obstacle to overcome in the preparation of the contour map was the correlation of strata from one well to another and from one part of the field to another. The difficulties of such correlations are doubtless familiar to anyone who has tried to work out the underground structure of any of the California fields. The Santa Maria field offers as much encouragement to successful study and mapping of the underlying oil-bearing formations as any other so far examined by the senior author, and so the effort has been made to delineate on the map all the details of structure furnished by the data available, and to supplement these details by showing for the untested areas what seem to be the most likely conditions of underground structure. It is very easy to make an ambiguous statement which will apply equally well to any conditions exposed by future development, no matter what they may be; but it is impossible to make an ambiguous map. However, it is deemed advisable to show the information in hand, incomplete as it is, on a map. Future development will doubtless add much to our knowledge of this field, and will show the inaccuracies of the contouring as here presented, but it is hoped that the benefits which may accrue to the operators from a knowledge of the general structure of the field will compensate in a measure for the errors in detail which are to be expected in a map based on data so incomplete.

THE WELLS.

AREAS DISCUSSED.

For convenience of discussion the proved portion of the Santa Maria field has been roughly divided into six areas, based largely on the geographic position of the wells. The following are the areas discussed: Hall-Hobbs-Rice ranch; Pinal-Fox-Hobbs; Pinal-Folsom-Santa Maria Oil and Gas-Escolle; Hartnell-Brookshire; Graciosa-Western Union; and eastern Western Union.

OIL ZONES.

Although in many instances detailed correlation from one well to another is impossible, four fairly well defined oil zones are believed to be recognizable in the Santa Maria field. Of these at least two are found in practically every part of the field, although all vary

more or less in thickness, composition, and yield from well to well. The most persistent zone in that part of the field which is best developed at the present time is the second, or B zone. Above this in many of the wells is zone A; in others zone C is penetrated below it. The upper zone in the eastern group of Western Union wells, although above what is supposed to be the horizon of B, is probably considerably above the A zone of the northern part of the field, where it appears to have no correlative.

With the exception of the lowest zone in the wells in the eastern part of the field and of a few others mentioned in the detailed discussion of the local areas, the oil zones appear to represent fractured portions of the shales, the interstices in the breccia or possibly joint cracks in the beds being the reservoirs for the storage of the oil. The exceptions to the brecciated productive zones are apparently typical sands and gravels.

HALL-HOBBS RICE RANCH AREA.

LOCATION AND STRUCTURE.

The area here discussed comprises the California Coast, Meridian, Coblentz, Santa Maria Oil Company (Keyser), Hall & Hall, New Pennsylvania, Rice ranch, and Dome properties and the northeastern part of the Hobbs lease, and occupies the ridges and canyons which extend northward from the east end of the main Graciosa Ridge. The wells are located on the northwestern flank of the Mount Solomon anticline, at or immediately northwest of the territory, in which it swings from a northeastward to a southeastward trend. In addition to the main anticline there appear to be one or more local flexures involved in the structure of the field, the Hobbs anticline and the syncline between it and the Mount Solomon anticline being the most prominent. The characteristics and extent of these features as they are believed to exist are portrayed on the contour map (Pl. X).

GEOLOGY OF THE WELLS.

Nearly all the wells in this area, with the exception of the Hall, Meridian, and Coblentz start down in the Monterey shale. Those farthest away from the top of the ridge, other things being equal, have to penetrate farthest through the Fernando clay, sand, and conglomerate. Up to the present time the greatest thickness of the Fernando penetrated before reaching the shale is 650 feet, and much trouble was experienced in going through it in this well, the formation being mostly sand. From the top of the Monterey shale to the bottom of the wells the rocks are largely blue and brown shales, with only here and there interbedded hard "shell" layers. In fact,

one log reports "no shell" until the first oil zone is reached. Wherever "shell" is penetrated accumulations of gas or oil or both are generally encountered. The shale seems to be somewhat more sandy in this area than farther west or in the Graciosa-Western Union region.

Three oil zones are recognizable in the area under discussion, although practically all the strata from the top of the uppermost zone to the bottom of the lowest are more or less petroliferous at one point or another.

The first productive zone (A) is penetrated at a depth of 1,600 to 2,100 feet, varying according to the position of the well geographically and relatively to the axis of the anticline. Its top is from 550 to 700 feet above the top of zone B in this area. Zone A is productive for a distance in the wells of 20 to more than 500 feet. Of course this does not mean that the beds are productive in any one well for the whole distance of 500 feet, but that throughout the zone alternating barren and productive beds occur at such close and as a rule irregular intervals as to preclude their practical differentiation. The productive measures in this first zone consist both of hard fractured shale or "shell" and more or less porous sandy layers. In at least one of the wells the oil accumulates only under the hard "shell" layers. Zone A is the only one penetrated by some of the wells farthest away from the anticlinical axis. In these wells it appears to be much more petroliferous than in wells higher up on the fold.

The second oil zone (B) is from 550 to 700 feet below the top of zone A, and its upper limit is about 300 or 400 feet above the top of zone C, although it can hardly be said to be distinct from C in all the wells, so rich in oil are some of the intervening strata between them. True sands of medium grain, in addition to the productive hard shale, yield the oil in this zone.

The third oil zone (C) is encountered in some of the deeper wells nearest the axis of the main anticline. This zone has been penetrated for as much as 150 feet, the whole distance being very rich in petroleum. It is overlain by a considerable thickness of black shale, also more or less petroliferous, between which and the rich zone is a thin, hard "shell" layer. The oil-yielding rock is a true sand, coarse in places and even becoming pebbly toward its base in certain portions of the area. To the coarseness of the material is doubtless due the great productiveness of the zone.

PRODUCT.

The oil in the Hall-Hobbs-Rice ranch area runs from 26° to 29° Baumé and is dark brown in color. Gas accompanies the oil and also occurs isolated under some of the more impervious "shell" layers in the shale. No water is reported in any of the wells.

The production of the wells ranges from 300 to something over 2,000 barrels per day. Those wells which penetrate the lowest or C zone are the best producers. It is said that where a number of wells are located comparatively near together the production of each well is largely dependent on whether or not the adjacent wells are producing, a fluctuation of 50 per cent resulting from this cause in some instances.

PINAL-FOX-HOBBS AREA.

LOCATION AND STRUCTURE.

The area comprising the Fox lease, the southwestern part of the Hobbs lease, and the northeastern portion of the Pinal property, occupies the ridge and two adjacent canyons which extend northward from the central portion of Graciosa Ridge. The wells are located in an area of considerable structural disturbance caused by the development of two local anticlines on the northwestern flank of the main Mount Solomon anticline. These two minor flexures have been named after the companies under whose property they are best developed. Although the position assigned to them on the map is more or less hypothetical, the evidence in favor of it is fairly complete, and their location explains some of the variations in production of adjacent wells.

GEOLOGY OF THE WELLS.

Practically all the wells within this area start in the Monterey shale, and this is the prevailing formation to their bottoms. Certain portions of the shale are burnt to a brick-red color by the combustion of their hydrocarbon contents, the burnt shale being encountered as low as 330 feet in one of the wells. The burning has so hardened the shale in places as to render drilling in them more difficult. A hard limestone "shell" layer was encountered in one of the wells just above the second (B) oil zone. Tar or asphaltum occurs in some of the wells at a depth of about 600 feet, in others at various depths from 200 to 1,200 feet. The tar is in many wells associated with black shale. Gas accumulations under "shell" and other impervious layers are of common occurrence both in the oil zones and locally in the barren overlying shale. Water is encountered in some of the wells at depths ranging from 150 to 270 feet. This occurrence is noteworthy, as the wells in the group to the east are, so far as known, quite free from water in the shale. Its occurrence in the Fernando sands and conglomerates is to be expected, but its presence in sands interbedded with the shale is unusual for this field.

The first oil zone (A) is penetrated in the wells in this area at depths ranging from a little more than 1,600 to 2,650 feet, or between 400 and 600 feet above zone B. (See Pl. X, p. 92.) Petroliferous strata occur in some of the wells above this horizon, but they are of

little consequence as regards production. The thickness of zone A in the wells ranges from 8 or 10 to nearly 150 feet, but several more or less important oil-bearing zones lie between this and the next lower (B) zone. The productive measures of zone A consist largely of brown shale, probably seamed or jointed in such a way as to afford a reservoir for the oil, although certain of the wells may obtain their product from fine-grained sands interstratified with the shale.

The second oil zone (B) is the most important one in this area, although it is underlain over at least a part of the area by zone C, which is apparently even more productive. The thickness of zone B is variable, but most of the wells penetrate from 50 to 150 feet of productive strata at this horizon. The oil-bearing beds are similar to those of zone A and appear to consist largely of hard shales, with some fine sands, although some excellent examples of a true siliceous sand are obtained in many of the wells. A hard limestone "shell" overlies zone B in one well.

The third oil zone (C) is penetrated by some of the deeper wells at a depth of about 300 to 400 feet below zone B. In one of the wells zone C appears to be missing, although a good flow of oil is reported from the same hole about 500 feet below where it should occur.

Water underlies oil-zone B in one of the wells and zone C in another. This occurrence of water below the oil, so common in most fields, is very rare in this one. Whether or not in the course of time water will follow up the oil in the productive zones is something that will be awaited with a great deal of interest. Some of the wells in the Santa Maria field have been stopped in the midst of productive strata for fear of encountering water farther down, but whether or not these fears were well founded has never been established.

PRODUCT.

The oil from this group of wells is of a dark-brown color and ranges in gravity from 24° to 28° Baumé, the lighter oil usually occurring in the wells nearest the main anticline; the average gravity is between 25° and 26°. Much gas is associated with the oil in all the wells.

The production of the individual wells ranges from 60 to 1,000 barrels per day, the latter amount coming from a hole very eccentric in its behavior, as shown by its yield of 200 barrels on some days and as high as 1,000 on others; the average daily production for this well is 300 barrels. With the eccentric well omitted, the maximum production is about 500 barrels per day. One well which produced 150 barrels from zones A and B added 350 barrels to its output when deepened to zone C.

PINAL-FOLSOM-SANTA MARIA OIL AND GAS-ESCOLLE AREAS.

LOCATION AND STRUCTURE.

The area discussed in this section comprises the Folsom lease, the southern part of the Pinal property, the central and southern portion of the Santa Maria Oil and Gas lease, and the Escolle property of the Union Oil Company. The wells are located on the west end of Graciosa Ridge and in the canyons on its sides. The region is largely covered by the Fernando sandstone and conglomerate "cap rock," although the Monterey shale is exposed in the side canyons. The structure underlying this part of the field is comparatively simple so far as known, the main Mount Solomon anticline, which plunges northwestward through its center, being the only fold of consequence immediately affecting the area. The mapping of the anticline near Escolle well No. 3 is based entirely on the evidence offered by the well logs, which is at variance with the northwesterly dips in the Fernando in the vicinity of Escolle wells Nos. 2 and 3.

GEOLOGY OF THE WELLS.

Those wells which start in the Fernando remain in this formation for distances ranging from a few feet to nearly 300 feet, the strata penetrated being sand and conglomerate. In the region of Escolle well No. 1 and Folsom well No. 1 the Fernando appears to be exceptionally deep, extending nearly 300 feet below the surface, and to consist largely of conglomerate. One of the wells reports red conglomerate at 30 to 90 feet below the surface; whether this is burnt shale so hardened as to come out of the well in fragments of considerable size or whether it is true water-worn material is not known. Asphaltum is reported at the base of the Fernando in some of the wells, and may also be seen at the contact between the Monterey shale and overlying beds at many places in this area. (See Pl. XI, *A*.) The channels through which this material has escaped from the shale are undoubtedly joint cracks, as veins of the hardened asphaltum may be seen in the shale beside the road leading up to Santa Maria Oil and Gas (Squires) well No. 4 and at other points in the field. From the base of the Fernando to the bottom of the wells the strata penetrated are practically all shale with a few hard "shell" layers, under which occur accumulations of gas and locally of oil.

A zone in which "shells" appear to be particularly abundant immediately overlies the first oil zone. Traces of tar and asphaltum are also reported in the shale at various depths. Two zones in which many hard limestone "shells" layers are encountered are reported from some of the wells; one of these is about 500 feet above the second oil zone (B), and the other immediately underlies it.

A. DARK-COLORED FOSSILIFEROUS BREA DEPOSIT OVERLYING MONTEREY SHALE.

Graciosa Ridge at Folsom well No. 3; Pinal camp on left and Santa Maria Valley in distance. Looking north. Photograph by Ralph Arnold.

B. SADDLE IN MONTEREY, FERNANDO, AND PLEISTOCENE BEDS.

Graciosa Ridge at Hartnell well No. 1, near Orcutt; Pleistocene on left, Fernando (Pliocene) in upper right, Monterey (Miocene) in saddle. Looking east. Photograph by Ralph Arnold.

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A. DARK-COLORE

Gneiss Ridge at Folsom

The first oil zone (A), which lies from 250 to 500 feet above zone B, is struck at depths ranging from 1,400 to 2,450 feet. Its thickness ranges from a few feet to about 50 feet; according to the logs it is lacking in some of the wells, the first oil being encountered in zone B. The oil-bearing strata in zone A are largely shale, which afford a reservoir for the oil, probably on account of their fractured condition. Beds of fine sand in this zone may also contain some of the petroleum.

The second oil zone (B), occurs at depths of 1,950 to 3,150 feet and is penetrated by all of the wells in this area. It ranges in thickness from nearly 50 to about 250 feet, in the wells; one of the wells, however, is said to encounter petroliferous beds intermittently from the top of zone B for a distance of 550 feet downward. The oil-bearing strata consist of alternating layers of hard shale and fine sandstone.

The third oil zone (C), occurs from 500 to 600 feet lower in the wells than zone B and consists of two parts, each from 25 to 50 feet thick, separated by a layer of shale of variable thickness; in one of the wells, however, the intervening shale is missing and the strata are richly impregnated with oil from the top of the zone for a distance of 250 feet downward, to a point where a 3-foot layer of water sand limits the productive zone. In practically all the wells in the field zone C is very rich, and nearly all the wells tapping it are fine producers.

PRODUCT.

The oil obtained in the area under discussion averages somewhat better than that in the area to the east, and has a gravity of 26° to 28° Baumé, with an average somewhere between 26° and 27°. As is common in other portions of the field, the gas pressure in most of the wells is high.

The production of the individual wells ranges from 100 to 2,700 barrels per day, the well yielding the latter amount being said to have had an initial daily output of 5,000 barrels for a short time. In one series of wells those down the dip are more productive than those nearer the axis of the anticline, the variation being at least partially accounted for by a thickening of the oil zone away from the axis.

HARTNELL-BROOKSHIRE AREA.

LOCATION AND STRUCTURE.

The area comprising the southern portion of the Hartnell tract and Brookshire property and the southeastern portion of the Radium lease is located on or adjacent to the ridge running northwestward from a point near the west end of Graciosa Ridge, and in the broad valley to the south. The major structural feature developed in the

beds underlying the area is a northwestward-plunging anticline which is here called the "Hartnell." There is both surface and underground evidence of its presence, but its exact location is, of course, only conjectural. As will be noticed on examining the map (Pl. X, p. 92) the northern flank of the anticline is much steeper than the southwestern, this fact apparently having a direct bearing on the productiveness of the wells penetrating this flank.

GEOLOGY OF THE WELLS.

The surface distribution of the formations in the immediate vicinity of the little swale on the ridge in which Brookshire wells Nos. 3 and 4 are situated is very interesting. The bottom of the swale is Monterey (Miocene) shale; unconformably overlying this on the south is fossiliferous Fernando (Pliocene) sandstone and conglomerate; immediately north of the swale is terrace-deposit (Pleistocene) sandstone. (See Pl. XI, *B*.) It has been suggested that such a condition is most easily explained by the presence of a fault through the swale, the downthrow being on the north. The logs of the wells in the immediate vicinity, however, offer evidence that such is not the case, but that the underlying Monterey strata, followed almost immediately north of the swale by fossiliferous Fernando beds, plunge steeply northward and are overlain unconformably by the low-dipping or practically horizontal terrace beds which are exposed on the ridge north of the swale. Some of the wells starting in the post-Monterey formations penetrate sand and gravel for a distance of more than 600 feet before entering the Monterey. Limestone, probably corresponding to the limy layers associated with fossiliferous beds at the base of the Fernando in the railroad cut north of Schumann, is reported as occurring next to the Monterey shale in one of the wells. Water is encountered in gravel at various horizons in the Fernando between the depths of 150 and 600 feet. Hartnell well No. 3 and Brookshire well No. 1 (the latter about half a mile northeast of the area under discussion), which penetrate the water-bearing Fernando, are used as water wells. From the base of the Fernando to their bottoms the wells penetrate blue and brown shale, and very rarely fine sandy layers. "Shell" strata, many of them underlain by gas and some by oil and gas, are encountered here and there throughout the shale.

The first oil zone (A) occurs about 400 feet above zone B, is struck at depths ranging from 2,150 to more than 3,000 feet, and is said to be from 2 to 5 feet thick. On examination of the material coming from this and the underlying productive zones, it is quite apparent that the oil must come from the joint cracks or interstices between the fragments of more or less fractured shale, as no true sands of sufficient coarseness to allow the rapid transmission of the oil have been encountered in the productive zones in the wells of this group.

Between the first zone and the one that has been recognized as the second, or zone B, are one or more productive zones 2 to 15 feet thick. No two wells show the same sequence of these zones and they probably represent places of local fracturing.

The second oil zone (B) is thought to be fairly constant throughout the area. It consists of alternating barren and productive layers of shale, some of the productive layers being from a few feet to as much as 20 feet thick. Below the main or upper part of this zone are other productive layers, some at least 200 feet below zone B. The oil-bearing measures in these zones, as in zone A, are probably nothing more or less than fractured portions of the shale.

PRODUCT.

The oil from the wells in this area runs from 24° to 26° Baumé, and is dark brown in color with the exception of that from one of the wells, which is said to be a reddish emulsion of oil and water. All the wells show much gas, the best producers, especially, being under heavy pressure.

The production of the individual wells in this group ranges from an initial output of 12,000 barrels per day in one well to a daily average of 150 barrels in another. The following statement concerning the production of Hartnell well No. 1, the greatest producer in the California oil fields, has been kindly furnished by Mr. Orcutt, of the Union Oil Company:

Well (Hartnell No. 1) started to flow over derrick through 8¼-inch and between this and 10-inch casing December 3, 1904. Gas pressure was very heavy, estimated at 400 pounds per square inch—was probably much higher, however. Oil was measured in an open ditch by use of a miner's-inch measuring box, and showed 31 miner's inches, or about 12,000 barrels per day. The flow continued for about sixty days and gradually weakened. September 1, 1905, the well was doing 3,069 barrels per day.

The oil was stored in earthen reservoirs, and the production to the above date is estimated at 1,500,000 barrels from this well alone. Up to August 15, 1906, the total production for the well was something over 2,000,000 barrels.

The gas accompanying the initial flow of oil was estimated at 4,000,000 cubic feet per day. After the well had been gotten under control it furnished gas for running 20 boilers for well-drilling rigs, and in addition supplied the town of Orcutt (population about 200) with gas for domestic purposes. At the present time it is still yielding a constant flow, which is used for many purposes in Orcutt.

GRACIOSA-WESTERN UNION AREA.

LOCATION AND STRUCTURE.

The wells at the northeast corner of the Graciosa and northwestern corner of the Western Union properties are located on the point of the ridge which runs southward for more than a mile from the main Graciosa ridge. The structure of the beds underlying the developed area is apparently simple, as they are on the southwestern flank of the hypothetical Newlove anticline. At least two minor

folds occur on this flank, one apparently passing through Western Union wells Nos. 21 and 22 and the other occurring from three-eighths to five-eighths of a mile farther northwest. The Newlove anticline as shown on the map is wholly hypothetical. It is the expression of the most plausible explanation of the relationship which is supposed to exist between the known Graciosa-Western Union and the eastern Western Union well areas. The surface evidence of the structure consists of a 10° SE. dip in the Fernando beds just north of the Graciosa wells, together with some more or less uncertain dips in the Monterey toward the head of the ridge, approximately parallel with which the anticline is supposed to run.

GEOLOGY OF THE WELLS.

The wells all start in the sands of the Fernando, penetrating this formation for 70 to 300 feet. No water is reported from this sand, but asphaltum is said to have been found at its base in one of the wells. From the base of the Fernando to the top of the main productive zone the formation consists of blue and brown shales with many hard "shell" layers, some beds of sticky shale, and rarely a little sandy material. Streaks of asphaltum are reported as occurring in the shale in some of the wells, and in others gas is present under some of the "shells."

The first oil zone (B of the northern part of the field) is reported from only one well, where it is nearly 200 feet thick and is encountered at a depth of about 2,075 feet. Gas is associated with the oil in this zone.

The second and important oil zone of this area (C) is struck at depths ranging from 2,670 to something more than 3,800 feet, and lies about 600 feet lower in the wells than zone B, which is apparently unproductive in most of the wells. According to the data in hand, the productive zone ranges in thickness from 18 to about 240 feet and consists of alternating light and dark flinty shales interbedded with varying amounts of sandy shale. No true sand, as ordinarily implied by the name, occurs in the productive zone of this area, so far as the writers were able to learn.

PRODUCT.

The oil from zone C runs from 25° to 27° Baumé, averaging well up between 26° and 27°, and has a brownish color. It comes from the wells at a temperature of about 95° F. and is usually accompanied by much gas. Certain of the wells, however, are said to show a comparatively low gas pressure.

The production of the individual wells ranges from 300 to 3,000 barrels per day, the flow of many being unusually strong. None of the wells have been allowed to produce up to their full capacity,

owing to the lack of storage and transportation facilities, so that even had they been down long enough for a thorough test (which is hardly the case, inasmuch as nearly all have been finished since 1904) no definite conclusions could be drawn concerning their lasting properties.

EASTERN GROUP OF WESTERN UNION WELLS.

LOCATION AND STRUCTURE.

The eastern wells of the Western Union Company are located near the head of one of the branches of the broad valley which extends east-northeastward from Harris Canyon, at Blake, and are about 5 miles southeast of Orcutt. They are from one-half to three-fourths of a mile east of the west property line of the company and close to the north line. Slightly more than half a mile to the northeast of the wells is the axis of the Mount Solomon anticline, from the southwestern flank of which the wells derive their oil. The structure in the immediate vicinity of the wells, as indicated by the logs (see Pl. X, p. 92), is more or less complicated, the general strike of the beds apparently changing abruptly from northwest to southwest immediately northwest of the group. Furthermore, a local flexure with northeast-southwest strike immediately underlies the developed territory, and a pronounced anticline (here named the "Western Union") with a steep northeastern flank lies just to the south. There is no surface evidence of the northeast-southwest disturbance, but the Western Union anticline is plainly to be seen in the Fernando beds. The dip of the beds on the southwestern flank of this fold ranges at the surface from 15° at the west end of the hill south of the wells to 10°, and possibly much less, one-half mile to the southeast. The maximum northeasterly dip of 45° occurs south of well No. 18, but the slope rapidly decreases both to the northwest and southeast. As nearly as could be ascertained from the available data, the production of the wells in this group supports the anticlinal theory of the accumulation of petroleum—that is, for an equal thickness of productive zone the wells near the axis of the anticline in the local flexure are more productive than those farther away from it.

GEOLOGY OF THE WELLS.

The wells start in soil, but soon enter the clay, sand, and conglomerate layers of the Fernando, which is the surface formation in this part of the field. The Fernando beds are penetrated for 100 to 250 feet, varying with the location of the well, the wells on the north, as would be expected after an examination of the surface geology, passing through it in the shortest distance. Water and quicksand were encountered in at least two of the wells in the lower portion of the Fernando; in another, asphaltum occurs at the base of the formation. From the base of the Fernando to the first oil zone the wells penetrate

blue and brown shales, largely the latter, interstratified with hard "shell" layers, under some of which are accumulations of gas.

The first oil zone is struck at a depth of 1,200 to 1,800 feet, and ranges in thickness from 12 to 75 feet, although in some of the wells sands are encountered at intervals for at least 250 feet below the top of the first sand. The oil sand is as a rule rather fine grained and is accompanied both above and below by shale and rarely by shell. In some of the wells the oil zone appears to be practically continuous sand for its entire thickness; in others, alternating sand and shale layers furnish the oil.

A second oil zone occurs about 1,200 feet below the first, the entire distance between the two being occupied by shale, with a few hard "shell" layers. Very little oil occurs at this horizon.

A third oil zone about 150 feet thick is penetrated 2,100 feet below the first, the formation between the second and third zones being practically all shale. Comparatively little oil was obtained from this zone in this part of the field, although it is thought to be the same as the one which is so productive in the Graciosa Western Union area only half a mile to the west. This may be accounted for by the general synclinal position of the eastern group between the Mount Solomon and hypothetical Newlove anticlines.

PRODUCT.

The oil in the first productive zone has an average gravity of about 19° Baumé and is very dark colored. Gas is associated with the oil, but no water has so far been reported from any of the wells.

The production of the wells in this group ranges from 5 to 154 barrels per day. The yield of some of the wells is fairly constant, showing only a small decrease in average daily output over a considerable number of months; in others, however, the yield is fluctuating.

LOMPOC FIELD.

LOCATION.

The developed territory within the Lompoc field, on which the following discussion is based, lies on the flanks of the Purisima Hills between the Cebada Canyon and Santa Lucia Canyon roads. Within it are located the Logan well of the Los Alamos Oil and Development Company; the Hill, Wise & Denigan, and Eefson wells of the Union Oil Company; and the abandoned wells of the Todos Santos, Coast Line, and Barca oil companies.

STRUCTURE.

The dominant structural feature of the field is the main anticline of the Purisima Hills. From surface evidence the location of the

anticline is believed to be that shown on the map (Pl. I, in pocket); from the evidence offered by the logs of the Hill and Logan wells the axis of the anticline, so far as it affects the oil-bearing beds of this part of the field, might better be drawn through Hill well No. 1, extending westward and eastward (swinging to the north in both directions) to the points where the "surface" anticline passes from the Fernando to the Monterey. In either location, however, the anticline has a steeply dipping northern flank and a low-dipping and probably undulating southern flank.

A fault, clearly seen on the east side of Cebada Canyon and traced by deposits of asphaltum over portions of the rest of its course, extends from a point a short distance east of Cebada Canyon northwestward at least as far as the brea deposits near Wise & Denigan well No. 1. This is clearly a reverse fault in the Cebada Canyon region, supposed Monterey diatomaceous shale being thrust up on the north over Fernando sandstone which lies south of the line, the dip of the fault plane being about 30° toward the north. Mr. Orcutt suggests that this fault probably causes the difference in yield between Hill wells Nos. 2 and 3. The sand is struck about 700 feet lower in No. 3 than in No. 2, and is barren in the former but productive in the latter. The dip in the strata (if the anticline affecting the oil sands passes south of well No. 2) might account for the difference in depth of the oil sand in the two wells, but it alone would hardly account for the difference in saturation of the sands. It is quite possible that the fault (which theoretically emerges somewhere near Hill well No. 4) passes downward at such an angle as to cut the oil sand between Hill wells Nos. 2 and 3, throws the sand down on the north, and, while acting as an outlet for the oil in the sand for some distance on its northern or upper side, effectively seals up the truncated end of the same sand on its southern or lower side. This hypothesis assumes a downthrow on the north, a condition exactly opposite to that shown at the surface in Cebada Canyon. Alternate upthrow and downthrow on the same side of a single fault occurring at different times are not unusual in the Coast Ranges, so that such an explanation is not only possible but probable. To conform to the prevailing conditions the downthrow must have been on the north in pre-Fernando and on the south in Fernando or post-Fernando time.

The logs of the Wise & Denigan wells indicate a more or less local anticline in the Monterey. Its axis passes near well No. 2 of this group, and probably extends in an east-west direction parallel to the major lines of structure in the hills immediately to the north. This occurrence suggests the probable gentle folding of the Monterey in the region south of the Purisima Hills, in a manner similar to that which takes place under Burton Mesa farther west.

GEOLOGY.

GENERAL STATEMENT.

All the productive wells in the Lompoc field start in the Fernando formation and penetrate its clays, sandstones, and conglomerates for distances ranging from 45 to 800 feet. The great variation in the thickness of the Fernando in adjacent wells (the beds over much of the territory being nearly horizontal, implies great inequalities in the surface of the underlying Monterey shale, and this in turn signifies a profound unconformity between the two formations. Water is encountered in the Fernando at various depths in the different wells.

From the base of the Fernando to the top of the oil sand the wells pass through shale (largely "brown," according to the logs). Hard siliceous "shell" layers are encountered here and there in this shale, and in one well hard limy "shells" were struck at only 1,180 feet from the surface. These limy layers are abundant in the formation just above the oil zone, but are not found in most of the wells above this horizon.

Oil and gas are found in minor quantities in the shale at various depths, from 500 feet down in some of the wells in the northern part of the developed area, although such occurrences are not recorded for the wells in the southern part.

BURNT SHALE.

One of the most interesting features of the geology of the Monterey shale in this area is the evidence that combustion has taken place within it at certain points about 1,000 feet below the surface. Mr. Orcutt, of the Union Oil Company, exhibited samples of red shale coming from depths of 950 and 1,040 feet below the surface in Hill well No. 1, which are identical in appearance and texture to the burnt shale found so abundantly in the bituminous areas of the Monterey on the north side of the Santa Maria field and in other fields throughout the State. Traces of petroleum were associated with the upper stratum of burnt shale in Hill well No. 1.

OIL ZONES.

The principal productive oil zone in the Lompoc field is struck at depths below the surface ranging from about 2,200 to more than 4,100 feet. In nearly all the wells the productive strata are overlain by a more or less prominent series of limy "shell" layers, which apparently act as barriers to the upward migration of the oil at the present time. The beds beneath these limy "shells" are true sands in most places, although in some of the wells these sands are interstratified with varying quantities of shale and limestone "shells." The thickness of the oil zone varies from about 160 to 700 feet, and a productive series of sands, shales, and "shells" is said to be penetrated for a

distance of 1,100 feet in one well. Either water sand, dry oil sand, or limy "shell" usually defines the base of the productive zone.

THE OIL.

Two grades of oil are struck in this field, one a black oil with a gravity of 18° to 24°, the other a brown to greenish oil of about 35° Baumé. The black oil is produced by most of the wells, the lighter variety coming only from the Logan well of the Los Alamos Oil and Development Company and the No. 3 Wise & Denigan well of the Union Oil Company. The relations of occurrence of the two grades are not known. One of the wells yields an emulsion of water and 20° oil, which is reddish brown in color as it comes from the well. This oil turns to the usual black color on separation of the water by settling.

PRODUCTION.

The production of the individual wells ranges from 100 to 1,000 barrels per day, the best producers averaging from 300 to 500 barrels. One of the wells which gave an initial output of 200 to 300 barrels at first, suddenly began flowing 1,000 barrels per day. This continued for a few days and then gradually fell off to 300 barrels, which it is still yielding. It is said that the wells, as a rule, are exceptionally steady producers, falling off but little in the two years since the field was first opened. Very few of the wells have been tried to their full capacity, so that it is probable that yields greater than those mentioned will be recorded when the field is fully tested.

ARROYO GRANDE FIELD.

LOCATION.

Drilling has recently shown that at least certain portions of the region north and northwest of Arroyo Grande, in the San Luis quadrangle, San Luis Obispo County, a short distance north of the area shown on Pl. I, are underlain by productive oil formations. The successful wells belong to the Tiber Oil Company, and are located on the west side of Price Canyon about 3 miles northeast of Pismo and 7 miles slightly east of south of San Luis Obispo. Although outside of the immediate area covered by this report the occurrence is so important in showing an extension of the Santa Maria district toward the northwest as to merit mention here.

GEOLOGY.

The geology of the San Luis quadrangle has been mapped and described by H. W. Fairbanks in the San Luis folio.[a] According to

[a] Copies of this folio, which is No. 101 in the series making up the Geologic Atlas of the United States, should be in the hands of every oil man or other person interested in the natural resources of this region; it may be obtained for 25 cents from the Director of the United States Geological Survey, Washington, D. C.

this work nearly all of the territory of the hills between San Luis Obispo Creek and the Arroyo Grande Valley, with the exception of a rather small area of Monterey volcanic ash, shale, and diatomaceous earth north of Pismo, is covered by the Pismo formation. This formation is composed of sandstone, some of which is asphaltic, and cherty diatomaceous beds, and is the equivalent of the lower part of the Fernando formation as described for the hills adjacent to the south side of the Santa Maria Valley. The Pismo is unconformably underlain by the Monterey shale, which outcrops on either side of it.

STRUCTURE.

According to Fairbanks, the Pismo area forms a low syncline, striking northwest and southeast, its flanks resting against the upturned Monterey.

OCCURRENCE OF THE OIL.

The oil is derived from a great thickness of productive sands which probably represent the base of the Pismo and which rest upon the upturned and more or less contorted shale of the Monterey. Its occurrence in beds occupying a synclinal position is worthy of note, as ordinarily synclines are not highly productive. The Monterey is the oil-bearing formation in the Santa Maria district, and it is the ultimate source of the oil in this field also. The migration of the oil probably took place along joint cracks in the shale, as was the case with the asphaltum in the Santa Maria and other fields. The oil, on reaching the upper limit of the shale passed across the plane of unconformity and accumulated beneath an impervious shale in the porous sands at the base of the Pismo. Where this porous layer approaches the surface the more volatile parts of the oil have escaped and there remains nothing but the bitumen, while the more deeply covered sands retain the oil in its lighter and liquid state. The migration of the oil, as in every similar case coming under the notice of the writers, has been accompanied by a loss of its volatile constituents and a consequent lowering of the gravity. This is evidenced by the fact that although the gravity of the oil from the Monterey formation in the Santa Maria field averages about 25°, that from the Pismo in the Arroyo Grande field is only 14°.

CONCLUSIONS REGARDING FUTURE DEVELOPMENT.

It seems almost certain that considerable portions of the Pismo formation toward the middle of the area northwest and north of Arroyo Grande will be found to be oil producing. This conclusion is based on the assumption that the Pismo of this region is underlain

by the oil-yielding Monterey. The surface evidence of such a condition is most conclusive. What effect local flexures either in the Monterey below the Pismo or in the Pismo itself will have on the production, only drilling will determine. According to Fairbanks's interpretation of the structure of the area, the depth at which the oil will be struck ought to decrease from the middle of the area toward both the northeast and southwest. The only well fully tested in the region yields 500 barrels of 14° oil per day, so that the prospects for the development of a good field are unusually bright.

As the Monterey shale underlying the Pismo of the Arroyo Grande field is continuous with the Monterey mapped in the Lompoc quadrangle northeast of the Santa Maria Valley, it is reasonable to suppose that there are considerable portions of this great belt of Monterey that will prove productive. The local structure is usually the determining factor in the accumulation of the petroleum, so that a thorough knowledge of this is essential to economical test drilling.

HUASNA FIELD.

The Huasna field lies east of the Arroyo Grande field and north of the Lompoc quadrangle. Prospect drilling is now going on in this region, but with what results the writers are not able to say. During a very hasty trip through this region in the summer of 1905 the senior writer noted great areas of Monterey shale, with some interbedded coarse granitic sandstones, in many places of considerable thickness. Such conditions are ideal for the accumulation of petroleum if the beds are not too sharply folded. This Monterey area is probably the continuation of that exposed in the northeastern part of the Lompoc quadrangle, and may connect the latter with the Monterey area east of Arroyo Grande and also with that covering the summit of the Santa Lucia Range a few miles east of San Luis Obispo. It is to be regretted that no maps adequate for showing the structure of the formations in the region east of the San Luis quadrangle and north of the Lompoc quadrangle are available. Without these it will be impossible to do for this region such detailed geologic and structural mapping as has already been done for the two quadrangles mentioned.

OIL OF THE SANTA MARIA DISTRICT.

ORIGIN.

There is no doubt that the petroleum in the Santa Maria district is indigenous to the Monterey shale. Bitumen is a characteristic part of that formation throughout its wide extent over an area covering hundreds of square miles, and there is no other formation

but the Eocene shales in which it is characteristic, or in which it occurs in appreciable quantity except locally, although there are numerous formations which would be capable of storing oil if any had originated in them. Moreover, the bituminous Monterey shale of the Coast Ranges does not occur consistently above or below any one formation from which the oil could have been derived. It lies unconformably upon ancient metamorphic rocks; granite and other igneous rocks; Jurassic, Cretaceous, or early Tertiary sediments; or conformably over lower Miocene beds, according to local conditions; and it is either not covered by later deposits or is buried by sediments of various ages, in different places.

The decision is therefore unavoidable that some ingredients of the Monterey shale gave rise to the oil, and the question arises what these were. The organic composition of the strata making up this formation is discussed on pages 38–43, where a number of animal and plant forms that may have contributed to the oil are enumerated. The writers are strongly of the belief that the petroleum was derived largely from the minute organisms, especially the plant organisms (diatoms), which are present in such abundance in these shales. The chemists Peckham and Clarke believe that the nitrogen present in the California oil proves its origin from animal substance. But it is not necessary to consider that this petroleum originated entirely from either animal or vegetable matter; it is more probably the product of remains of both kinds combined, much of the nitrogenous material being furnished by animal tissue.

Other small organisms of a low order present in the Monterey shale besides the diatoms are Foraminifera and Radiolaria, both orders of marine animals. They became embedded in the mass of the organic and adventitious silt material of the deposit at the sea bottom, and their bodies were thus preserved with the hard parts and may have become a source of hydrocarbons and nitrogen for the petroleum. The fact that the limestone and calcareous shale of the Monterey are usually very bituminous suggests the conclusion that the Foraminifera were great oil formers, inasmuch as these rocks are thought to be made up largely of foraminiferal remains, although of course the calcareous strata may owe their petroliferous character to their porosity. In many places the body of the limestone is full of minute specks of oil contained in cavities about the size of the interior of foraminiferal skeletons, and these specks give the impression that the oil is not far from its point of origin. Albert Mann, of the United States Department of Agriculture, makes the suggestion that possibly Foraminifera originally made up a greater part of the shales than now appears and that their easily destroyed calcareous tests were leached out, the soft parts adding their quota to the total amount of petroleum formed and owing to their animal character helping to

cause the relatively high percentage of nitrogen found in the California oils.

Fish skeletons are sometimes found in the shale, and flat impressions, large and small, that appear to be the scales of fish are abundant and very characteristic of certain portions of this formation, seeming to show that fish remains were in sufficient abundance to add at least something to the oil and to supply a portion of the nitrogen. On the other hand, these fossilized parts may have been originally separated from the tissue before they dropped to the ocean bottom or before being buried in the deposit, as by far the greater number of fish are believed to die violent deaths and to serve as food for larger fish or other animals.

Other animal organisms which were present and which may have contributed hydrocarbons and nitrogen were sponges, mollusks, and crustaceans—such as crabs and possibly ostracods. The impressions of seaweed occur in the shale but sparingly, probably because plants of this kind are restricted in habitat to shallower water than that in which it is believed the greater part of the Monterey was laid down, so that it is not probable that these plants have been large contributors to the material of the oil.

It is certain that there was a sufficiency of organic material included with the Monterey deposits to give rise to a vast quantity of petroleum, as is proved by a rough estimate based on low calculations of the amount of such material present. If the area covered by the Monterey formation in the Santa Maria district, including territory surely covered by it whether the formation now outcrops there or not, be taken as 800 square miles and the thickness of the formation as half a mile, the total volume of the deposit would be 400 cubic miles. These figures are low, especially in view of the fact that the average thickness and the areal extent of the formation were much greater when the oil began to be accumulated than at present. If we regard for the moment the diatoms alone to be the source of the oil, and only 1 per cent of the formation to be made up of these organisms, there would be 4 cubic miles of diatoms; and if we suppose further, simply as a rough guess, that these forms gave rise to an amount of petroleum equaling 1 per cent of their volume, we would have 1,000,000,000 barrels of oil as the amount distilled within the Monterey in this district, or more than thirty-three times the total production of oil in California for 1904, or eight times the production in the United States for the same year. According to Albert Mann, who has recently made an extensive study of diatoms, these plants when living secrete algal wax or oil in amounts varying from 0.75 per cent to as much as 4 per cent of their total volume. The amount of petroleum that might be derived from the diatoms is entirely unknown; but if the figure assumed hypothetically as

being 1 per cent is too liberal, it would seem that the low estimates of the amount of diatomaceous material present and the complete ignoring of the other important organic sources for oil in the shale, would still cause the estimate to be conservative.

In considering the question, What kind of organic material has a character most favorable for producing oil? the relative rate of putrefaction is important. Plants have the advantage in respect to their slower rate of decomposition. David White inclines to the view that plants are more favorable to the production of oil, largely for this reason. He says that putrefaction, which is largely a bacterial process, goes on more rapidly in animal tissue, while vegetable material has a tendency to turn into hydrocarbons. The slow decomposition of the protoplasm contents of the diatom frustule is especially significant. F. J. Keeley, of the Philadelphia Academy of Natural Sciences, says as follows in a letter:

> The only point I can think of that might have any bearing on the question of the relation of diatoms to petroleum is the fact that the organic matter of diatoms does not appear to decompose and become dissipated quickly after death, as is the case with most low organisms. It is well known that diatoms kept in water will show the shrunken contents for years, and Ehrenberg noted the presence of such organic contents in old fossil diatoms from Hanover, while J. Brun reports a similar observation in a fossil deposit from Holland.

It is worthy of note that many of the round white diatom tests of the soft Monterey shale contain minute specks of black that appear like bituminous material derived in situ from the diatom. These specks, however, are present in but a small proportion of the tests and there is no proof that the black substance has not come from infiltration and deposition in the slight hollow of the shell. Thin sections of the shale reveal small black filaments that appear to be carbonaceous material.

It is probable that the ooze at the sea bottom in Monterey time was being deposited very rapidly. The idea of rapid accumulation of the deposits of diatoms, aided by the accession of organic and detrital material of other kinds, is quite in keeping with the well-known faculty of these organisms for quick and abundant reproduction; and it is not only in keeping with but an essential corollary of the fact that deposits of such vast thickness were formed during middle Miocene time. This rapid accumulation created further favorable conditions for the production of oil, inasmuch as the organic substance that reached the sea floor became quickly buried without sufficient time intervening for decomposition to go very far. Thus the contents of the diatom frustules and all the other plant and animal remains became included in the body of the deposit.

The alkalinity of the shale may have been another favoring factor. As the deposits grew, salts of the sea water were probably included

in the porous mass and they may have acted as preservatives of the organisms to some extent.

As regards the age of the oil, it is stated by F. W. Clarke[a] that the process of formation of the oil from organic sources may not be slow, but, on the other hand, comparatively rapid. It is usually thought, however, that the process of distillation is slow and is continued during a long time. The petroleum in the Monterey may have been formed immediately after the deposit was laid down, or the production of it may be still in progress. There is evidence, however, in the presence of burnt shale in a Pleistocene deposit (see p. 52), in the old and eroded deposits of asphalt, and in the presence in certain asphalt deposits of the bones of extinct Pleistocene mammals[b] which were caught in tar springs in Pleistocene time, that much of the oil at least was formed in the Monterey and disseminated to the surface a long time ago. The accumulation and dissemination of the oil has probably gone on continuously ever since its first formation, the two processes taking place simultaneously. There may be portions of the formation from which the hydrocarbon content has not yet been extracted in the form of oil, whereas other portions may no longer contain any of the oil in its original disseminated condition. The metamorphism that gave rise to the harder shales may have had the effect of driving out the oil more completely than it has been separated from the softer shale, and thus aided its accumulation, although this is conjectural.

The general conclusion is that in the Santa Maria district the organic material in the Monterey shale that may have acted as the source of the oil was without a doubt adequate in amount for the production of the vast quantity of petroleum now present, and that the forms included in greatest abundance, the diatoms, were the chief source, although animals and perhaps other plants also contributed largely.

PHYSICAL PROPERTIES.

GENERAL STATEMENT.

The Santa Maria district yields four distinct grades of petroleum, in addition to the heavy oil which flows from springs or collects as asphalt deposits. These petroleums vary widely in their physical and chemical properties and as a consequence are utilized in many different ways, the lighter oils usually for refining, the heavier for fuel, road dressing, etc.

The oil as it comes from the wells contains varying quantities of gas, often amounting to a considerable percentage. The two prod-

[a] The data of geochemistry (in preparation for publication by the United States Geological Survey).
[b] Bull. U. S. Geol. Survey No. 309, 1907, pp. 154-155.

ucts are usually separated at the wells, the gas being utilized for heat or directly for power and the oil being run into tanks. This tank oil still contains gas, most of which, however, gradually passes off on exposure to the air, with a consequent lowering of the gravity of the oil. Before transportation by steamer it is necessary to pass the oil through a partial refining process for the removal of the lighter, volatile, more dangerous constituents; this is done at present in the refineries at Port Harford and Gaviota.

COLOR AND ODOR.

Nearly all of the oil in the Santa Maria district is dark brown in color. The exceptions are the black oil from the Arroyo Grande field, the reddish emulsion from one of the wells in the Hartnell-Brookshire area, and the brown to greenish oil found in certain of the wells in the Lompoc field. The heavier oil is the darker; the lighter grades show the greenish hues. The darkest oil in the Santa Maria field proper is the 19° petroleum from the wells in the eastern Western Union group. Some very dark oil is also said to come from the Lompoc field.

The heavy oil gives off an aroma not unlike some grades of lubricating oil, and, doubtless owing to the absence of hydrogen sulphide in solution, has little of the disagreeable odor common to that from some of the other California districts. In this district the lighter the oil, as a rule, the sharper and less agreeable is its odor.

GRAVITY.

The gravity of the oil ranges from 14° to about 35° Baumé. The heaviest oil (14°) comes from the Arroyo Grande field; 18° to 24° oil from the Lompoc field; 19° oil from the eastern group of Western Union wells; 24° to 29° oil from the Santa Maria field; and 35° oil from the Los Alamos Oil and Development Company's well and one of the Wise & Denigan wells. The average gravity of the oil from the Santa Maria field proper is between 26° and 27°, thus putting it well into the class of valuable refinable petroleums.

VISCOSITY.

The relative viscosity of several of the oils from the Santa Maria district, together with similar data for other California oils, is shown in the table on page 116.

CHEMICAL PROPERTIES.

Few data concerning the chemical properties of the oil from the Santa Maria district are at present available for publication except

those found in Bulletins Nos. 31 and 32 of the California State Mining Bureau. The analyses of Santa Maria oil contained in these bulletins were made by H. N. Cooper, and, together with those of oils from some of the other California districts, are copied in the table below.

The only definite information concerning the ultimate composition of the oil is contained in a table by P. W. Prutzman[a] showing the incidental constituents of California crude oil. This author states that a Santa Maria oil of 17° (probably from the eastern group of Western Union wells) contained 0.43 per cent of nitrogen, no sulphur, and 8.37 per cent of asphaltene. The freedom of the Santa Maria oil from sulphur is one of its chief and valuable characteristics.

The following table[b] contains analyses of four oils from the Santa Maria district, accompanied by analyses of twelve other California oils for purposes of comparison. The oil of analysis No. 3 in the table is the most characteristic of the average product of the Santa Maria field.

Following the table are distillation tests.

Chemical analyses of California petroleum.

[By H. N. Cooper, chemist. Samples collected by Marion Aubury, field assistant.]

No. of analysis.	Name of company.	County.	District.	Gravity.	Specific gravity of crude at 15° C. (about 60° F.).
				° *B.*	
1	Western Union Oil Co	Santa Barbara	Western Union	20	0.9337
2	do	do	Carreaga	34.6	.8508
3	Pinal Oil Co	do		27.6	.8882
4	Union Oil Co. of California	do	Lompoc	16.2	.9574
5	Sea Cliff Oil Co	do	Summerland	14.9	.9665
6	King Refining Co	Kern	Kern River field	13	.9792
7	I. W. Shirley	Los Angeles	Middle field	16.5	.9559
8	Southern Pacific Oil Co	Kern	McKittrick	18.5	.9425
9	Home Oil Co	Los Angeles	Whittier	20.7	.9291
10	Brea Canyon Oil Co	Orange	Fullerton	23	.9147
11	Los Angeles Pacific Rwy. Co	Ventura	Santa Paula	27.3	.8900
12	Union Oil Co. of California	do	Adams Canyon	28.9	.8814
13	California Oilfields (Limited)	Fresno	Coalinga	31.3	.8680
14	Home Oil Co	do	do	34.1	.8530
15	Los Angeles Pacific Rwy. Co	Ventura	Timber Canyon	35.1	.8481
16	Pacific Coast Oil Co	Los Angeles	Pico Canyon	37.3	.8367

[a] Bull. California State Mining Bureau No. 32, 1904, p. 224.

[b] For a detailed description of the methods used in obtaining the data recorded in this table the reader is referred to Bull. California State Mining Bureau No. 31, p. 1; idem, No. 32, 1904, table opp. p. 230; or to Bull. U. S. Geol. Survey No 309, 1907, pp. 205–208.

Chemical analyses of California petroleum—Continued.

No. of analysis.	Flash.	Viscosity. At 15° C. (about 60° F.). Seconds.	Viscosity. At 15° C. (about 60° F.). Seconds divided by 27½ or water=1.	Viscosity. At 85° C. (185° F.). Seconds.	Viscosity. At 85° C. (185° F.). Seconds divided by 27½ or water=1.	Sulphur.	Calorific value of dry samples.[a]	Calorific values per cubic centimeter.
	°					*Per cent.*		
1	Below 15	1,060	38.40	77½	2.81	2.08	10,369	9,907
2	15	47⅞	1.72	29⅞	1.07	.60	10,825	9,203
3	Below 15	90	3.27	37⅞	1.36	1.56	10,543	9,364
4	21	Over 1,800	Over 65.00	227	8.23	4.43	10,258	9,822
5	Above 70	Over 1,800	Over 65.00	108	3.91	.44	10,348	10,001
6	Above 70	Over 1,800	Over 65.00	410	14.86	.....	.....	.....
7	Above 70	Over 1,800	Over 65.00	78	2.83	.85	10,437	9,976
8	32	1,100	39.85	54	1.96	.77	10,402	9,804
9	26	393	14.24	43	1.56	.....	.....	.....
10	Below 15	264	9.56	41½	1.50	.94	10,581	9,678
11	Below 15	61⅞	2.23	34½	1.24	.....	.....	.....
12	Below 15	162½	5.91	37	1.34	.48	10,647	9,384
13	Below 15	56	2.03	32½	1.18	.38	10,739	9,321
14	Below 15	28½	1.03	25½	.99	.06	10,598	9,040
15	Below 15	45⅞	1.66	31⅛	1.13	.....	.....	.....
16	Below 15	38½	1.40	29½	1.07	.28	11,141	9,322

No. of analysis.	Distillation. Percentage. Water.	Up to 100° C.	100°-150° C.	150°-200° C.	200°-250° C.	250°-300° C.	300° C. to asphalt. A.	300° C. to asphalt. B.	Asphalt.	Loss or gain.
1	None.	0.9	6	10.5	9.3	11	39.5	.....	22	−0.8
2	None.	8.6	16	12	13.4	10.8	23	7.4	8	− .8
3	None.	8.2	17.7	12.1	9.4	9.1	29.7	.....	12	−1.8
4	7	1.3	3.9	5.5	7.7	18.3	34.3	.....	20.6	−1.4
5	.7	0	0	.1	10	17.4	45.5	.....	23.5	−1.9
6	None.	0	0	0	0	22.5	37.5	6.9	31.1	−2
7	.8	0	0	0	7.6	13.9	40	14.5	21.8	−1.4
8	None.	0	4.2	8.9	8.7	20.2	27.5	7.5	22.5	− .5
9	None.	0	4.2	9.6	14	14.7	23	16.8	15.7	−2
10	None.	4.2	13.9	8.9	9.7	18.3	24.2	5	13.3	−2.5
11	None.	9.3	16.5	11.8	7.7	9.1	31.8	.....	13	− .8
12	None.	4	14.1	9.1	9.3	10.1	43	.....	9.8	− .6
13	None.	10.4	13.8	10.5	10.3	17.5	20.8	7.3	9.1	− .3
14	None.	5.5	30.6	21.5	25.4	8.1	5	.....	4.1	+ .2
15	None.	15.3	15	9.5	9.9	9.9	28	.....	10.6	−1.8
16	None.	10.5	20.4	13.8	13	11.1	16.9	6.8	6.8	− .7

No. of analysis.	Distillation. Gravity of preceding fractions at 15° C. (about 60° F.). Up to 100° C.	100°-150° C.	150°-200° C.	200°-250° C.	250°-300° C.	300° C. to asphalt. A.	300° C. to asphalt. B.
1	.....	0.7596	0.8087	0.8538	0.8875	0.9167	.....
2	0.7185	.7683	.8028	.8354	.8574	.8788	0.8822
3	.7123	.7617	.8132	.8583	.8899	.9085	.....
4	.....	.7737	.7906	.8316	.8613	.8992	.....
5	.....	.....	.....	.8516	.8840	.9347	.....
6	.....	.....	.....	.....	.8901	.8997	.8938
7	.....	.....	.....	.8625	.8849	.9021	.9053
8	.....	.7760	.8235	.8427	.8976	.8982	.8985
9	.....	.7756	.8313	.8672	.8991	.9210	.9166
10	.7252	.7701	.8172	.8597	.8937	.8955	.9062
11	.7228	.7724	.8202	.8613	.8901	.9154	.....
12	.7250	.7736	.8111	.8388	.8547	.8778	.....
13	.6906	.7630	.8041	.8382	.8774	.8866	.9062
14	.7395	.8074	.8396	.8919	.9227	.9374	.....
15	.7002	.7639	.8015	.8321	.8624	.8875	.....
16	.7472	.7659	.8040	.8359	.8606	.8870	.8720

[a] To convert calories into British thermal units, multiply by 1.8.

Proximate analysis of a Santa Maria oil.[a]

[Gravity, 16.9° Baumé.]

	Per cent.	Gravity (°B.).
DISTILLATION.		
Below 150° C.	1.0	.....
150° to 270° C.	24.0	39.5
Above 270° C.	31.1	.....
Asphalt, grade D	41.9	.....
Loss	2.0	.....
CALCULATED ANALYSIS.		
Total gasoline	2.7	55
Kerosene	16.8	41
Middlings and lubricants	36.6	.....
Asphalt, by volume[b]	41.9	.....
Loss	2.0	.....

[a] Prutzman, P. W., Bull. California State Mining Bureau, No. 32, 1904, Table 25.
[b] By weight (154 pounds per barrel), 46.2 per cent.

The following analyses of oils from the Santa Maria district have been kindly furnished by Prof. Edmond O'Neill, of the University of California, who writes concerning them as follows:

I do not know the exact locations of the wells from which these oils were derived, but they are from the first wells opened in the Santa Maria property [probably the Hartnell or the Santa Maria Oil and Gas Company lease]. There is very little difference in the character of oils from all this district, except in the proportion of light constituents and the corresponding percentage of sulphur. Most of these oils contain water, which seems to be either in a state of fine emulsion, or possibly in some feeble form of hydration—that is, frequently the water will not settle out on standing, even by centrifugalizing—nor will it all be driven off at a temperature of 100° Centigrade; but at a somewhat higher temperature it seems to be given off almost with explosive violence.

Analyses and tests of six samples of oil from wells near Santa Maria.

[Made by Edmond O'Neill.]

ANALYSES.

	No. 3.	No. 4.	No. 5.
Gravity at 15.5° C. (=60° F.)	0.891	0.894	0.893
Gravity in degrees Baumé	27.800	27.600	27.500
Flash point, open tester	(a)	(a)	(a)
Flash point, closed tester	(a)	(a)	(a)
Burning point, open tester	23° C.=73.4° F.	22° C.=71.6° F.	21° C.=70° F.
Gasoline precipitate (asphaltine, etc.) .....per cent	0.6	0.3	0.8
Sulphur .....do	1.57	1.59	1.56
Calorific value .....calories	10,260	10,363	10,229
Calorific value .....B. T. U.	18,468	18,653	18,415

	No. 6.	No. 7.	No. 13.
Gravity at 15.5° C. (= 60° F.)	0.897	0.908	0.926
Gravity in degrees Baumé	26.800	24.800	21.670
Flash point, open tester	(a)	(a)	(a)
Flash point, closed tester	(a)	(a)	(a)
Burning point, open tester	21° C.=68° F.	20° C.=68° F.	24° C.=75° F.
Gasoline precipitate (asphaltine, etc.) .....per cent	0.7	1.6	3.0
Sulphur .....do	1.61	2.09	1.8
Calorific value .....calories	10,284	18,375	8,078
Calorific value .....B. T. U.	18,512	18,676	14,541

[a] Under 15° C.=60° F.

Analyses and tests of six samples of oil from wells near Santa Maria—Continued.

RESULTS OF DISTILLATION.

	No. 3.	No. 4.	No. 5.	No. 6.	No. 7.	No. 13.
Water, per cent by volume..	1.2	0.2	Trace.	Trace.	Trace.	10.8
Benzines, boiling point under 150° C. (302° F.):						
Per cent	24.5	22.1	20.2	23.5	18.5	16.8
Gravity Specific	.745	.740	.740	.752	.752	.742
Gravity Baumé	60°	61.°2	61.°2	52°	52°	60.°8
Kerosene, boiling point 150° C.–250° C. (302° F.–482° F.):						
Per cent	21.5	20.5	21.5	18.7	18.5	22.1
Gravity Specific	.8345	.821	.818	.823	.822	.843
Gravity Baumé	39	41.8	42.5	41.4	41.4	37
Lubricants, boiling point 250° C.–350° C. (482° F.–662° F.):						
Per cent	19.0	22.8	19.2	20.0	25.5	17.2
Gravity Specific	.905	.889	.898	.897	.895	.899
Gravity Baumé	25.3	28.2	26.6	26.6	27	26.4
Lubricants, boiling point above 350° C. (666° F.):						
Per cent	23.0	22.7	20.3	25.5	22.5	16.2
Gravity Specific	.917	.905	.924	.917	.903	.906
Gravity Baumé	23.2	25.3	22	23.2	25.6	25
Asphaltum:						
Per cent	10.8	11.7	8.8	12.3	15.0	16.9

ASSOCIATED HYDROCARBONS.

NATURAL GAS.

Throughout the Santa Maria district wherever any oil has been found it is invariably accompanied by considerable quantities of natural gas; indeed, this form of hydrocarbon is somewhat more widely distributed than the oil, occurring in many places in the shale above the oil zones and in some wells which have yielded no petroleum. The pressure of the gas varies from zone to zone and from well to well. The greatest pressure so far recorded was in Hartnell well No. 1, where, according to Mr. Orcutt, it was over 400 pounds per square inch during the initial flow of oil and gas. Most of the gas is utilized for the generation of heat or of power direct in gas engines. Some of it is utilized for domestic purposes in the field and the immediate vicinity.

ASPHALT.

Great deposits of asphalt are associated with the petroleum-bearing and later formations over certain portions of the Santa Maria district. The asphalt (in the broader sense of the word) within the district occurs in several different ways—as veins penetrating the Monterey shale and later formations; as impregnations of the shale, sands, or gravels in or overlying the Monterey; and as more or less impure effusions at the surface. The more important deposits are in the hills northwest of Arroyo Grande; in the region of Asphaltum and La Zaca creeks, east of Sisquoc; in Graciosa Ridge; and in the vicinity of Redrock Mountain. These deposits have been described

in detail by George H. Eldridge,[a] and are mentioned at various places throughout this bulletin; further discussion of them is therefore unnecessary.

TECHNOLOGY OF PRODUCTION AND UTILIZATION.

OIL COMPANIES OF THE SANTA MARIA DISTRICT.

The following is a statement of the oil operations in the Santa Maria district, compiled from all data available up to January 1, 1907:

Oil companies and wells in Santa Maria district.

Company.	Field.	Oil wells.			
		Productive.	Abandoned.	Drilling.	Total.
Angio-Californian Oil Syndicate	Lompoc			1	1
Associated Oil Co	Arroyo Grande			1	1
Barca Oil Co	Lompoc		1		1
Brookshire Oil Co	Santa Maria	4	[b]1	1	6
California Coast Oil Co	do		1		1
California Coast Oil Co. (Union Oil Co.)	do	3			3
California-Newlove Oil Co	Arroyo Grande			1	1
Casmalia Ranch Oil and Development Co	Santa Maria		1		1
Claremont Oil Co	do		[b]1	1	2
Coast Line Oil Co	Lompoc		1		1
Coblentz Oil Co	Santa Maria			1	1
Crown Oil Co	Arroyo Grande			1	1
Crystal Oil Co	do			1	1
Diamond Oil Co	Santa Maria				
Dome Oil Co	do	1		1	2
Graciosa Oil Co	do	6		2	8
Hall & Hall Oil Co	do	1		1	2
La Grande Oil Co	Arroyo Grande			1	1
Laguna Land Co	do			1	1
Lompoc Oil Developing Co	Lompoc				
Los Alamos Oil and Development Co	do	1	2		3
Las Flores Land and Oil Co	Santa Maria				
McNee Oil Co	Arroyo Grande			1	1
Meridian Oil Co	Santa Maria			1	1
National Oil and Transportation Co. (Associated Oil Co.).	do			1	1
New Huasna Oil Co	Arroyo Grande			1	1
Oak Park Oil Co	do			1	1
Pennsylvania Oil Co	Santa Maria		1	1	2
Perpetual Oil Co	Arroyo Grande			1	1
Pacific Oil and Transportation Co. (Associated Oil Co.).	Santa Maria		1		1
Palmer Oil Co	do	1			1
Pinal Oil Co	do	11		3	14
Radium Oil Co	do		1		1
Recruit Oil Co. (Escolle and Newhall)	do		2	2	4
Rice Ranch Oil Co	do	2		1	3
Santa Barbara Oil Co	Santa Ynez			1	1
Santa Lucia Oil Co	Arroyo Grande			1	1
Santa Maria Oil Co. (Union Oil Co.)	Santa Maria	1		2	3
Santa Maria Oil and Gas Co. (Union Oil Co.)	do	4	1	3	8
Santa Ynez Valley Development Co	Santa Ynez				
Southern Pacific Co	Santa Maria			1	1
Standard Oil Co. (pipe lines, storage, etc.)	do				
Stillwell Oil Co	do				
Syndicate Oil Co. (Union Oil Co.)	do			1	1
The Oil Co	do		1		1
Tiber Oil Co	Arroyo Grande	1		2	3
Todos Santos Oil Co	Lompoc		1		1
Traders' Union Oil Co	Santa Maria		1		1
Union Oil Co.:					
Burton lease	Lompoc			1	1
Eefson lease	do	2	1	1	4
Folsom lease	Santa Maria	5		3	8

[a] The asphalt and bituminous rock deposits of the United States: Twenty-second Ann. Rept. U. S. Geol. Survey, part 5, 1901, pp. 209–452, pls. 25–58, figs. 1–52.

[b] Water well.

Oil companies and wells in Santa Maria district—Continued.

Company.	Field.	Oil wells.			
		Productive.	Abandoned.	Drilling.	Total.
Union Oil Co.—Continued.					
Fox lease	Santa Maria	5		1	6
Hartnell lease	do	2	[a]1	1	4
Hill lease	Lompoc	2	1	1	4
Hobbs lease	Santa Maria	8		2	10
Newlove	do			5	5
Wise & Denigan	Lompoc	8			8
Waldorf well	Santa Maria		1		1
Western Union Oil Co	do	26	3	2	31
Yakima Oil Co. (Lucas) (Associated Oil Co.).	do		1		1
		94	25	55	174

WELL DRILLING.

The wells in the Santa Maria district are among the deepest oil producers in the world, one of them reaching a depth of over 4,400 feet. Except at three or four wells, where rotary drills have been used to penetrate the soft sands and shales near the surface, all of the drilling has been done with the standard rig. The casing used ranges in diameter from 12 to 16 inches at the top down to 4½ inches, and in some wells, it is believed, even smaller, at the bottom. The cost of the deeper wells runs in general from $12,000 to $20,000, but several of the deepest are said to have cost even more than the latter figure.

Owing to the close texture of the shale, it is usually possible to carry the hole down for a considerable distance below the casing without danger of caving. Wherever the wells penetrate the soft Fernando beds for any considerable distance much trouble is experienced, but otherwise the drilling in the field is said to be as a rule comparatively easy.

PRODUCTION.

The production of oil in the Santa Maria region has been increasing rapidly in the last four or five years, but the figures of actual production do not fully indicate the increase in the capacity of the district. Lack of storage capacity, inadequate transportation facilities, and the low price of crude petroleum are factors which have kept down the amount produced and marketed. Well drilling has been going on steadily ever since the field was opened, but only a few companies have pushed their production up to the limit for any length of time.

Nearly all of the oil so far produced in the district has come from the Santa Maria field. The production of the district, including the Santa Maria, Lompoc, and Arroyo Grande fields, for the last five years is as follows:

Production of crude petroleum in Santa Maria oil district, 1902—1906.[a]

[Barrels of 42 gallons each.]

1902	99,283
1903	178,140
1904	1,367,174
1905	2,565,966
1906	4,906,513
	9,117,076

The estimated maximum capacity of the district January 1, 1907, is 40,400 barrels per day.

STORAGE CAPACITY.

The storage facilities of the district consist of steel and wooden tanks and open earthern reservoirs. The reservoirs are located only in the field and are used only temporarily or in cases of emergency. The total storage capacity of the district, not including the open reservoirs, is 1,464,000 barrels.

TRANSPORTATION FACILITIES.

The oil from the Santa Maria district is distributed by means of pipe lines, tank cars, and some of it eventually by tank steamers. The principal pipe lines of the district are four connecting the field with Port Harford and one running from the Western Union wells to Gaviota. The rail lines available are the Southern Pacific at Gaviota, Casmalia, and Betteravia, and the Pacific Coast at Carreaga and Orcutt. Tank steamers of the Associated, Standard, and Union oil companies take the product from Port Harford or Gaviota.

The following is a summary of the principal pipe lines in the district:

Pipe lines in Santa Maria oil district.

Company.	From—	To—	Distance.
			Miles.
Coast Oil Transport Co	Graciosa wells	Oil Port	34
Graciosa Oil Co	Wells	Casmalia	8
Los Alamos Oil and Development Co	do	Carreaga	
Pacific Oil and Transportation Co	Orcutt	Gaviota	51
Pinal and Brookshire oil companies	Wells	Graciosa station	2
Do	do	Betteravia	7
Standard Oil Co	Orcutt	Port Harford	32
Do	Western Union wells	Orcutt	7
Do	Hall, Dome, Pinal, and Brookshire wells.	do	3
Standard Oil Co. (2 lines)	Pacific Coast Oil Co.'s tanks.	Port Harford	
Union Oil Co	Orcutt	do	32
Do	do	do	32
Do	Lompoc field	Orcutt	16
Do	Escolle and Santa Maria Oil and Gas Co.'s wells.	do	3
Do	Fox, Hobbs, Folsom, and other wells.	do	3
Do	Reservoirs Nos. 1, 2, and 3	do	4
Western Union Oil Co	Wells	Carreaga	4

[a] Compiled from data furnished by the different operating companies.

REFINERIES.

The principal refineries utilizing the oil from the Santa Maria district are as follows:

California Petroleum Refineries, Limited.—The refinery of this newly organized company is now in course of erection at Oil Port, south of Port Harford. It is said that the initial capacity of this refinery will be about 7,000 barrels per day, and that all the usual products will be refined.

Pacific Oil Transportation Company.—The refinery of this company is located at Gaviota, and consists of nine stills with a capacity of 1,050 barrels of crude oil per day. The principal products are illuminants and fuel residue.

Standard Oil Company.—The plant of this company is located at Point Richmond, Contra Costa County, and is said to consist of 19 stills with a capacity of 5,000 barrels of crude oil and 4,000 barrels re-run per day. The products are illuminants, lubricants, and coke.

Union Oil Company of California.—The main refinery of this company is located at Oleum, Contra Costa County, and consists of a number of stills capable of producing illuminants, distillate, and asphalt.

UTILIZATION OF THE OIL.

Most of the oil from the Santa Maria district is refined, the lighter products being used for illuminants and for the direct generation of power in gas engines, and the heavier products and unrefined heavy oil for fuel, lubricants, road dressing, etc. With the exception of a very small amount used locally, all the oil is sent out of the district, the greater part of the product at present, it is believed, going to the refineries near San Francisco. Contracts recently made in South America, Japan, and the Hawaiian Islands indicate that within a short time much of the product of the district will be exported.

RÉSUMÉ.

The Santa Maria oil district, comprising the Santa Maria, Lompoc, Arroyo Grande, and Huasna fields, occupies the central and northern portions of the Lompoc and Guadalupe quadrangles, northern Santa Barbara County; the southern part of the San Luis quadrangle, southern San Luis Obispo County, and a small part of the unmapped area between the Lompoc and San Luis quadrangles.

The larger part of the district is a basin region inclosed between two divisions of the Coast Ranges—the San Rafael and Santa Ynez mountains—and the Pacific Ocean. The formations in this basin have undergone less disturbance than in the mountains and the conditions in it are good for the accumulation of oil.

The formations involved in the geology of the district include the Franciscan (Jurassic?) sandstone, shale, glaucophane schist, jasper, and intruded serpentine; Knoxville (lower Cretaceous) conglomerate, sandstone, and shale; pre-Monterey (which may include both Cretaceous and older Tertiary) conglomerate, sandstone, and shale; Tejon (Eocene) sandstone, shale, and conglomerate; Vaqueros (lower Miocene) conglomerate, sandstone, and shale; Monterey (middle Miocene) diatomaceous and flinty shale, limestone, calcerous shale, and volcanic ash; Fernando (Miocene-Pliocene-Pleistocene) conglomerate, sandstone, and shale; and Quaternary gravel, sand, clay, and alluvium. The sedimentary formations of Tertiary and early Quaternary age have a combined maximum thickness of at least 13,200 feet.

A variety of igneous rocks of Cretaceous and Tertiary age, mostly intrusive, outcrop over small areas.

The Monterey shale (middle Miocene) is the original and chief oil-bearing formation, the petroleum having originated and remained in it in large quantities. Some has escaped by seepage and collected in the overlying Fernando formation or the Quaternary terrace deposits, or has been dissipated. The oil is supposed to accumulate in fractured zones and porous sands in the lower portion of the Monterey, where brittle shale predominates, anticlines furnishing the most favorable conditions for accumulation. The Monterey shale is in large part of organic origin, being especially rich in diatoms, and the oil is supposed to be a product of the plant and animal remains inclosed in it. The quantity of these remains originally deposited with this formation is sufficient to account for a vast amount of derived oil.

Two structural systems prevail in the district, the features in the northeastern portion striking northwest and southeast, those in the southern portion striking east and west, and those in the intervening region trending in a direction intermediate between the two. Few faults of importance were noted in the field. The productive territory lies in a region of more or less gentle folds in the central part of the area, most of the wells being located along or near anticlines.

The wells range in depth from 1,500 to more than 4,000 feet. In the Santa Maria and Lompoc fields they obtain oil from zones of fractured shale, and possibly in certain places from sandy layers in the lower portion of the Monterey formation. The production of the individual wells ranges from 5 to 3,000 barrels per day, the average being between 300 and 400 barrels. The oil ranges in gravity from 19° to 35° Baumé, the greater part of it being about 25° to 27°. In the Arroyo Grande field the oil comes from sandstone at the base of the Fernando and is of 14° gravity. There is in all these fields much undeveloped territory which offers great promise of being

highly productive. The conditions affecting the presence of oil have been discussed for individual areas and those places enumerated in which the conditions seem favorable for its accumulation.

There are 52 oil companies interested in the district; 11 of these own all the producing wells. Of the 174 wells in the district 94 are productive, 55 are drilling, and 25 are abandoned. The total production of the field up to January 1, 1907, was 9,117,076 barrels; the production for 1906 alone was 4,906,513 barrels.

PLATES XII TO XXVI.

PLATE XII.

Tejon (Eocene) Fossils.

(Unless otherwise indicated all figures are natural size.)

Fig. 1. *Cardium brewerii* Gabb. Type. Right valve; altitude 61 mm. View of exterior. Pal. California, vol. 1, 1869, pl. 24, fig. 155. A common species in the Eocene of the Santa Ynez Mountains.

Fig. 2*a*. *Crassatellites collina* Conrad. U.S.N.M. 165312. Left valve; longitude 87 mm. View of exterior. San Julian ranch (4507). Characteristic of this horizon.

Fig. 2*b*. View of anterior end of same specimen.

Fig. 3. *Crassstellites collina* Conrad. U.S.N.M. 165312. Hinge. Same locality as fig. 2.

Fig. 4. *Pecten* (*Chlamys*) *yneziana* Arnold. U.S.N.M. 165313. Paratype. Altitude 52 mm. View of exterior. San Julian ranch (4507). Characteristic of this horizon.

Fig. 5*a*. *Ficus mamillatus* Gabb. U.S.N.M. 165319. Altitude 31 mm. View of back. North of Sudden (4518). Characteristic of this horizon.

Fig. 5*b*. View of top of same specimen.

Fig. 6. *Turritella uvasana* Conrad. U.S.N.M. 165327. Altitude of imperfect specimen 25 mm. Aperture view. North of Sudden (4578). Characteristic of this horizon.

TEJON (EOCENE) FOSSILS.

PLATE XIII.

Knoxville (Cretaceous) and Tejon (Eocene) Fossils.

(Unless otherwise indicated all figures are natural size.)

Fig. 1. *Aucella piochii* Gabb. U.S.N.M. 30831. Right valve; altitude 25 mm. View of exterior. Knoxville (lower Cretaceous) formation, East Fork Tepusquet Creek (4173). Characteristic of the lower Cretaceous throughout the Coast Ranges.

Fig. 2. *Aucella piochii* Gabb. U.S.N.M. 30831. Left valve; altitude 15 mm. View of exterior, × 2. Same locality and horizon as fig. 1.

Fig. 3*a*. *Aucella piochii* Gabb. Left valve; altitude 27 mm. View of exterior. Bull. U. S. Geol. Survey No. 133, 1895, pl. 4, fig. 6.

Fig. 3*b*. Exterior of right valve of same specimen. Op. cit., pl. 4, fig. 7.

Fig. 4. *Venericardia planicosta* Lamarck, U.S.N.M. 164973. Left valve; longitude 84 mm. Eocene, Little Falls, Wash. This is the most widespread and characteristic Eocene species in the world.

Fig. 5*a*. *Turritella* (*martinezensis* Gabb) var. *? lompocensis* Arnold. Paratype. Altitude of fragment, 30 mm. Back view. Same locality as fig. 8.

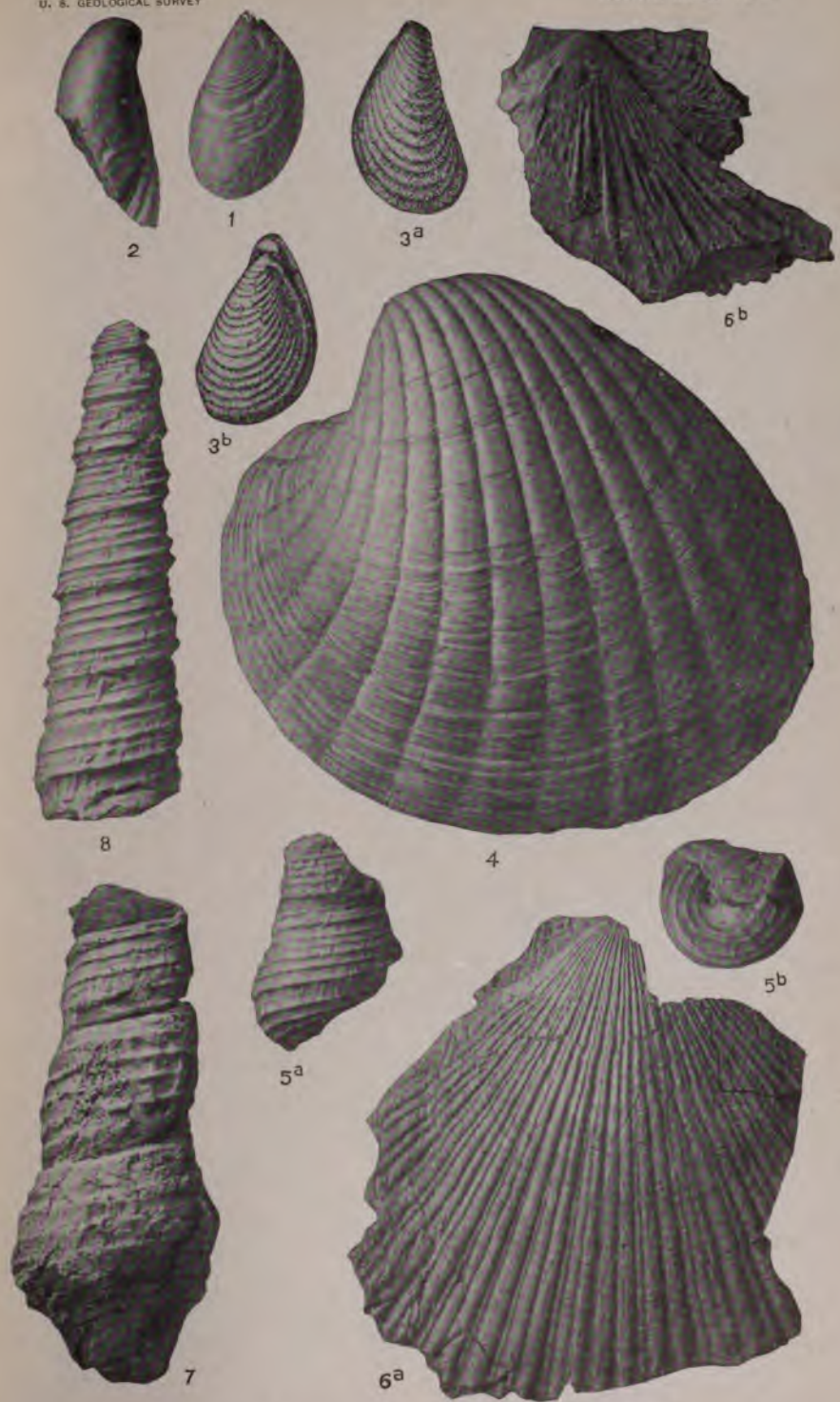
Fig. 5*b*. Basal view of same specimen.

Fig. 6*a*. *Pecten* (*Chlamys*) *yneziana* Arnold. U.S.N.M. 165313. Type. Right valve; altitude 64 mm. View of exterior. San Julian ranch (4507). Characteristic of this horizon.

Fig. 6*b*. Same species. Length of hinge of right valve 25 mm.

Fig. 7. *Turritella uvasana* Conrad. U.S.N.M. 165326. Altitude of imperfect specimen 68 mm. Aperture view. San Julian ranch (4507). Characteristic of the Eocene throughout the Coast Ranges.

Fig. 8. *Turritella* (*martinezensis* Gabb) var. *? lompocensis* Arnold. U.S.N.M. 165316. Type. Longitude 68 mm. View of back. Southwest of Lompoc (4509).



KNOXVILLE (CRETACEOUS) AND TEJON (EOCENE) FOSSILS

PLATE XIV.

Tejon (Eocene) Pelecypoda.

(Unless otherwise indicated all figures are natural size.)

Fig. 1*a*. *Ostrea idriaensis* Gabb. U.S.N.M. 165318. Left valve; altitude 114 mm. View of exterior. North of Sudden (4518). Characteristic of this horizon.

Fig. 1*b*. View of exterior of right valve of same specimen.

Fig. 2. *Phacoides cumulata* Gabb. U.S.N.M. 165328. Right valve; altitude 10 mm. View of exterior, × 4. Three miles north of Sudden (4518); also known from type locality of Tejon formation.

1a

2

1b

TEJON (EOCENE) PELECYPODA.

PLATE XV.

VAQUEROS (LOWER MIOCENE) FOSSILS.

(Unless otherwise indicated all figures are natural size.)

FIG. 1*a*. *Purpura vaquerosensis* Arnold. Collection of Delos Arnold. Type. Altitude 100 mm Aperture view. Lynchs Mountain, Monterey County, Cal.

FIG. 1*b*. Back view of same specimen.

FIG. 2. *Modiolus yneziana* Arnold. U.S.N.M. 165324. Type. Right valve; altitude 31 mm. View of exterior, × 2. San Julian ranch (4504). Characteristic of this horizon.

VAQUEROS (LOWER MIOCENE) FOSSILS.

PLATE XVI.

Vaqueros (Lower Miocene) Fossils.

(Unless otherwise indicated all figures are natural size.)

Fig. 1. *Pecten* (*Lyropecten*) *magnolia* Conrad. U.S.N.M. 165317. Right valve; altitude 155 mm. View of exterior, $\times \frac{1}{2}$. San Julian ranch. A characteristic Vaqueros species.

Fig. 2. *Ostrea eldridgei* Arnold. U.S.N.M. 165307. Left valve; altitude 100 mm. View of exterior. Mouth of Ballard Canyon, 2 miles south of Santa Ynez (4478). Characteristic of this horizon.

Fig. 3. *Turritella ineziana* Conrad. U.S.N.M. 165321. Altitude 120 mm. View of side. Ten miles west of Santa Ynez (4514). Characteristic of this horizon throughout the Coast Ranges.

1

2

3

VAQUEROS (LOWER MIOCENE) FOSSILS.

PLATE XVII.

Vaqueros (Lower Miocene) Pelecypoda and Brachiopoda.

(Unless otherwise indicated all figures are natural size.)

Fig. 1. *Pecten* (*Pecten*) *vanvlecki* Arnold. U.S.N.M. 165305. Type. Right valve; altitude 64 mm. View of exterior. Mouth of Ballard Canyon, 2 miles south of Santa Ynez (4478). Characteristic of this horizon.

Fig. 2. *Pecten* (*Pecten*) *vanvlecki* Arnold. U.S.N.M. 165306. Paratype. Left valve; altitude 72 mm. View of exterior. Mouth of Ballard Canyon, 2 miles south of Santa Ynez (4478). Characteristic of this horizon.

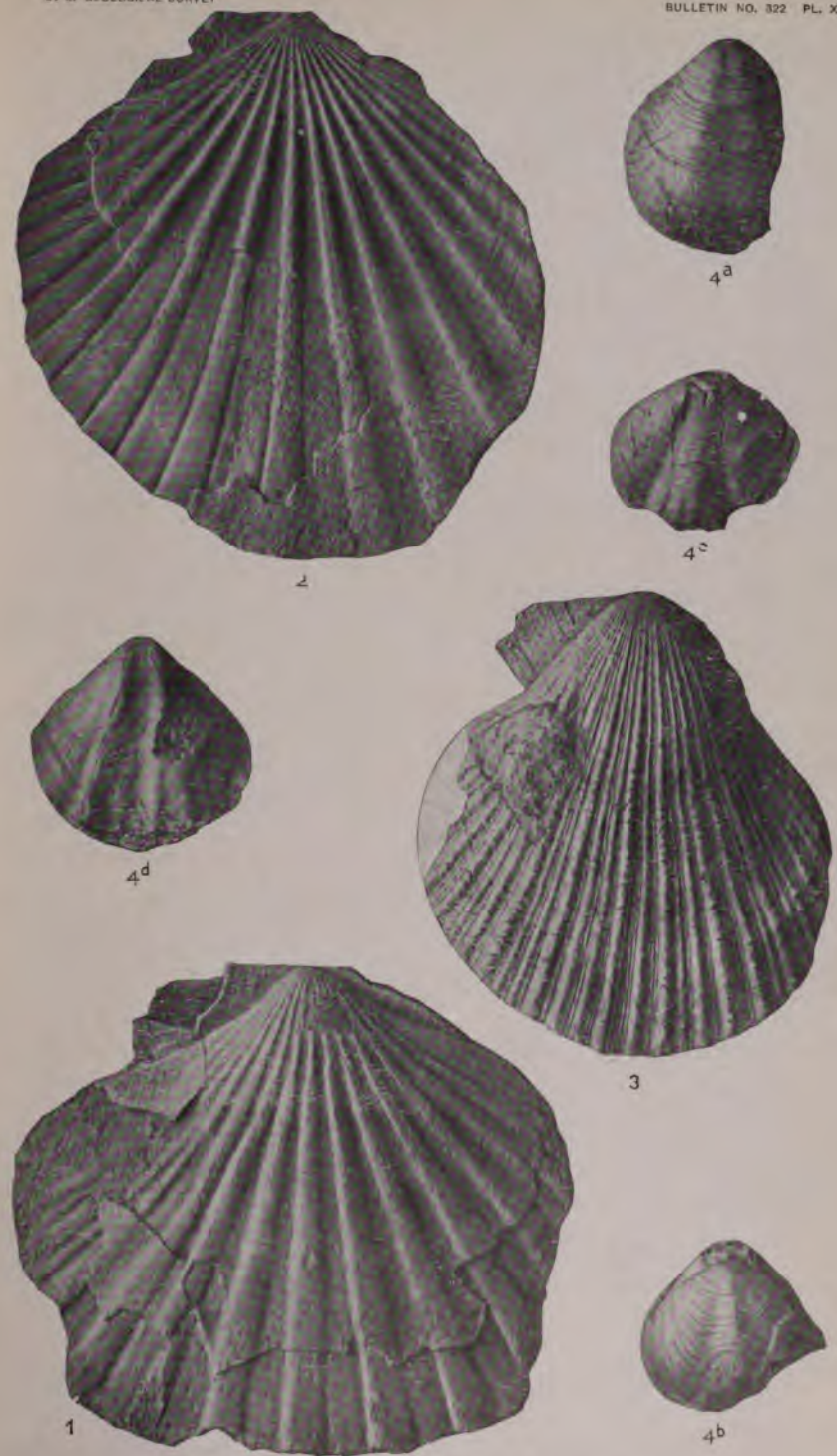
Fig. 3. *Pecten* (*Chlamys*) *sespeensis* var. *hydei* Arnold. U.S.N.M. 165308. Left valve; altitude 60 mm. View of exterior. Mouth of Ballard Canyon, 2 miles south of Santa Ynez (4478). Characteristic of this horizon.

Fig. 4*a*. *Terebratalia kennedyi* Dall. U.S.N.M. 165325. Type. Ventral valve; altitude 26 mm. View of exterior. Lime quarry 5 miles southwest of Lompoc (4521). Characteristic of this horizon.

Fig. 4*b*. Dorsal valve of same species; altitude of fragment 18 mm. View of exterior.

Fig. 4*c*. Dorsal valve of same species; altitude 19 mm. View of exterior.

Fig. 4*d*. Ventral valve of same species; altitude 28 mm. View of exterior.



VAQUEROS (LOWER MIOCENE) PELECYPODA AND BRACHIOPODA.

PLATE XVIII.

Vaqueros (Lower Miocene) Pelecypoda.

(Unless otherwise indicated all figures are one-half natural size.)

Fig. 1. *Pecten* (*Lyropecten*) *crassicardo* Conrad. U.S.N.M. 164967. Exterior of valve, showing characteristic sculpture; altitude 90 mm. Ojai Valley, Ventura County, Cal. This species ranges throughout the Miocene, being commoner in the lower part in southern California, in the upper part in central California.

Fig. 2. *Pecten* (*Amusium*) *lompocensis* Arnold. Collection of California Academy of Sciences. Holotype. Mold of interior of left valve; altitude 105 mm. Four miles south of Lompoc.

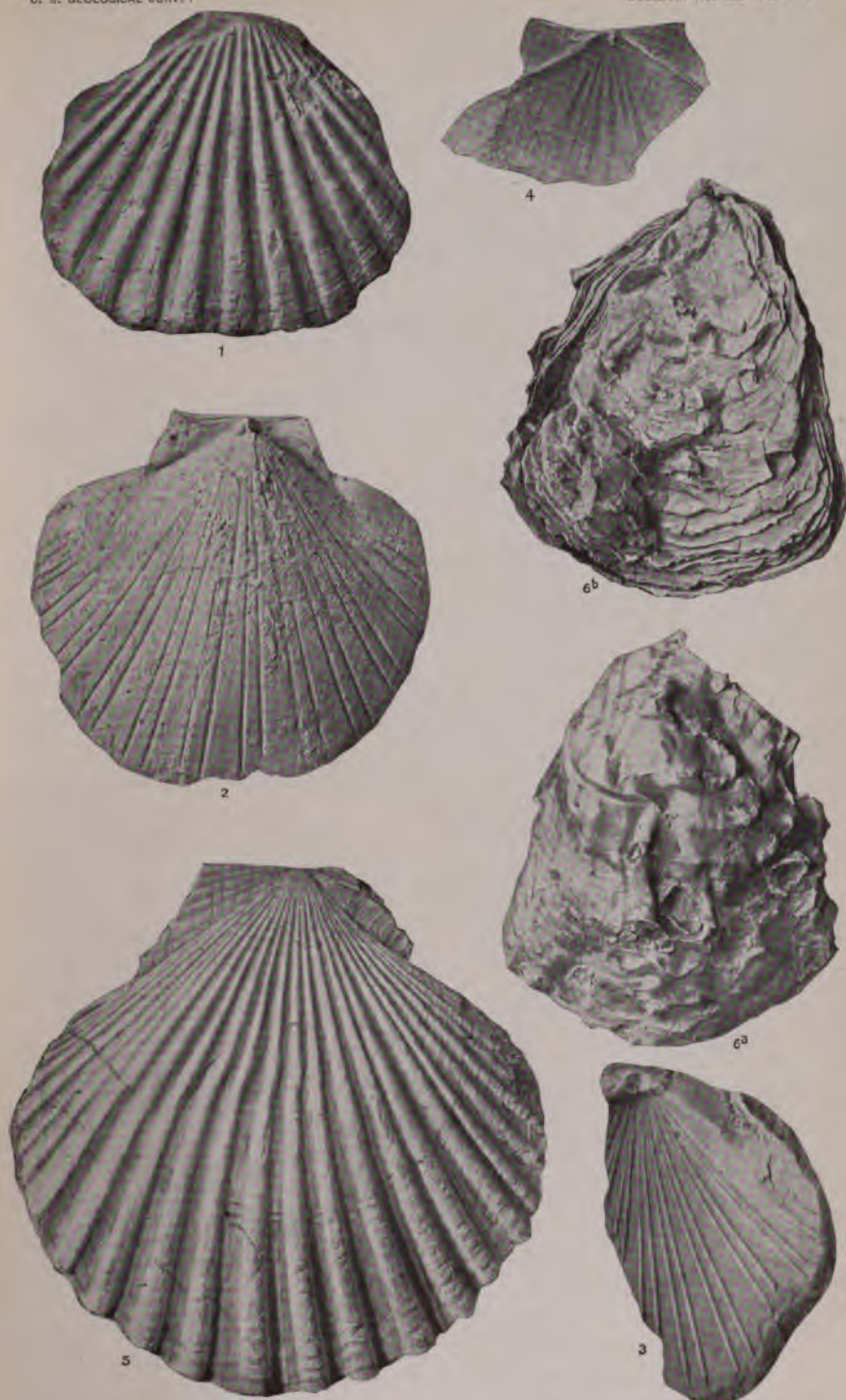
Fig. 3. *Pecten* (*Amusium*) *lompocensis* Arnold. U.S.N.M. 164852. Paratype. Interior of a portion of left valve; altitude 90 mm. Ojai Valley, Ventura County, Cal.

Fig. 4. *Pecten* (*Amusium*) *lompocensis* Arnold. Collection of California Academy of Sciences. Paratype. Imperfect mold of interior of right valve; hinge line 42 mm. Same locality as fig. 2.

Fig. 5. *Pecten* (*Lyropecten*) *bowersi* Arnold. Collection of University of California. Type. Exterior of slightly imperfect right valve; altitude 150 mm. Santa Ynez Canyon.

Fig. 6*a*. *Ostrea eldridgei* Arnold. U.S.N.M. 165320. Left valve; altitude 114 mm. View of exterior. El Jaro Creek (4519). Characteristic of this horizon.

Fig. 6*b*. View of exterior of right valve of same specimen.



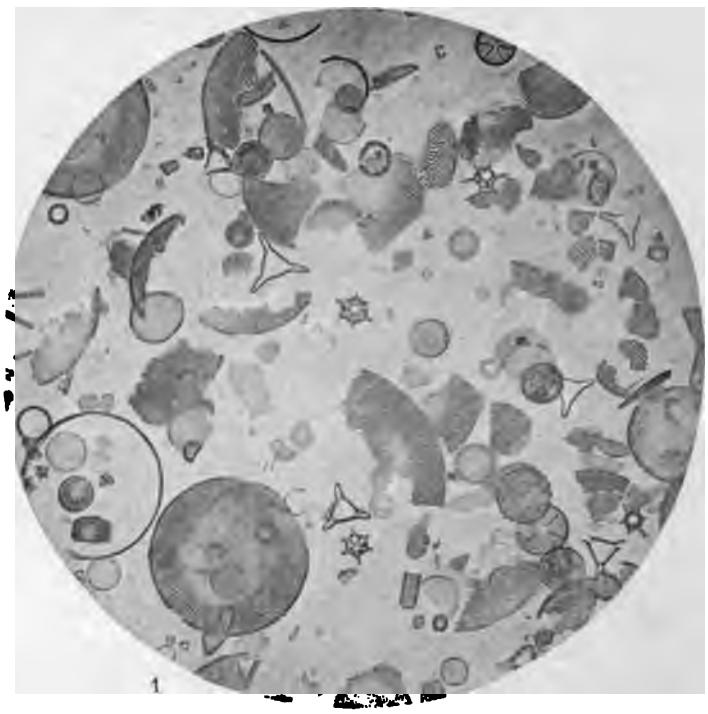
VAQUEROS (LOWER MIOCENE) PELECYPODA.

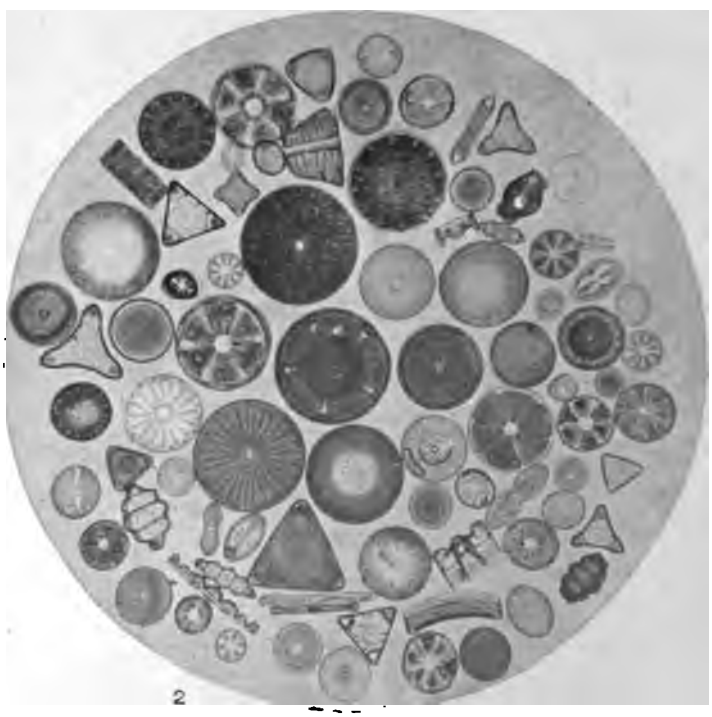
PLATE XIX.

Monterey (Middle Miocene) Diatoms.

Fig. 1. Photomicrograph of slide of partially cleaned diatomaceous shale material from the Lompoc quadrangle, × 100. All the larger individuals and fragments are *Coscinodiscus oculus iridis* Ehrenberg.

Fig. 2. Photomicrograph of slide of diatoms from the Monterey shale at Santa Monica, Los Angeles County, Cal , × 60. Nearly all the species shown on this slide occur in the diatomaceous deposits in the Santa Maria district.





MONTEREY (MIDDLE MIOCENE) DIATOMS.

PLATE XX.

Monterey (Middle Miocene) Diatoms.

Fig. 1*a*. *Actinoptychus undulatus* Ehrenberg.

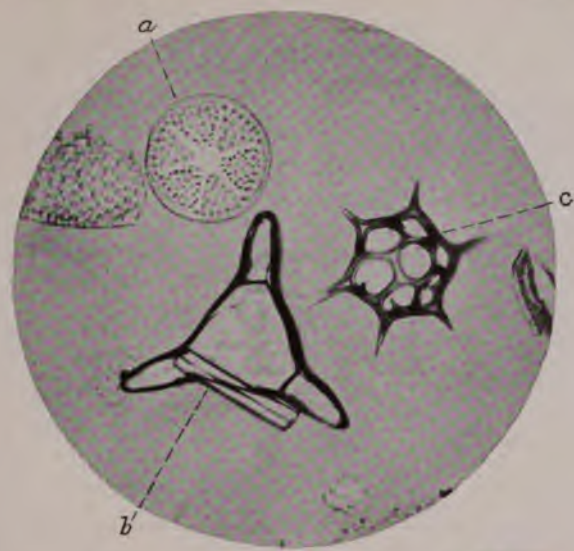
Fig. 1*b*. *Lithodesmium cornigerum* Brun.

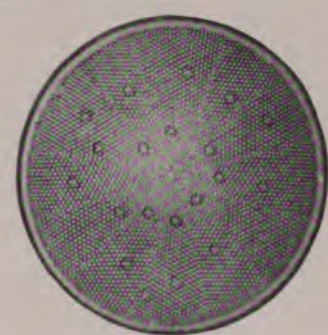
Fig. 1*c*. *Dictyocha gracilis* (not a diatom; nature unknown). Enlargement to 1,000 diameters of a portion of the slide shown in Pl. XIX, fig. 1.

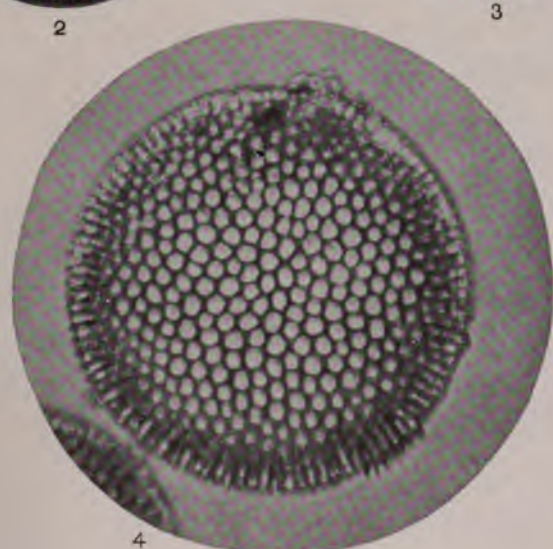
Fig. 2. *Coscinodiscus obscurus* A. S., × 1,000. From the Monterey shale of the Santa Maria district.

Fig. 3. *Coscinodiscus subtilis* Ehrenberg, × 1,000. From the Monterey shale of the Santa Maria district.

Fig. 4. *Coscinodiscus robustus* Grev., × 1,000. From the Monterey shale of the Santa Maria district.







MONTEREY (MIDDLE MIOCENE) DIATOMS.

PLATE XXI.

Fernando (Pliocene) Gasteropoda.

(Unless otherwise indicated figures are natural size.)

Fig. 1. *Trochita radians* Lamarck. U.S.N.M. 165310. Maximum diameter of fragment 20 mm. View of top, × 2. Fugler Point asphalt mine, near Gary (4475). Characteristic of the upper Miocene and lower Pliocene of this region.

Fig. 2. *Priene oregonensis* Redfield (young). U.S.N.M. 165262. Altitude 46 mm. Aperture view. Waldorf asphalt mine (4473). Also known recent.

Fig. 3. *Lunatia lewisii* Gould. U.S.N.M. 165264. Young specimen; altitude 23 mm. Aperture view, × 2. Waldorf asphalt mine (4473). Also known recent.

Fig. 4. *Thalotia caffea* Gabb. U.S.N.M. 165298. Latitude 29 mm. Back view. Fugler Point asphalt mine, near Gary (4475). Also known recent.

Fig. 5. *Thalotia caffea* Gabb. U.S.N.M. 165297. Latitude of fragment 21 mm. View of side of fragment, slightly tilted up. Same locality as fig. 4.

Fig. 6. *Lymnæa alamosensis* Arnold. U.S.N.M. 165426. Type. Altitude 6 mm. Aperture view, × 6. Fresh-water beds, 1 mile southeast of bench mark 425, Los Alamos Valley.

Fig. 7. *Lymnæa alamosensis* Arnold. U.S.N.M. 165426. Young specimen; altitude 3.5 mm. Same locality as fig. 6.

Fig. 8. *Cadulus fusiformis* Sharp and Pilsbry. U.S.N.M. 165267. Longitude 10 mm. Side view, × 3. Waldorf asphalt mine (4473). Known also recent.

Fig. 9. *Cancellaria crawfordiana* Dall var. *fugleri* Arnold. U.S.N.M. 165322. Type. Altitude 22.5 mm. Aperture view, × 2. Fugler Point asphalt mine, near Gary (4475). Characteristic of this horizon.

Fig. 10. *Ocinebra micheli* Ford var. *waldorfensis* Arnold. U.S.N.M. 165261. Type. Altitude 11 mm. Aperture view, × 3. Waldorf asphalt mine (4473).

Fig. 11. *Turritella cooperi* Carpenter. U.S.N.M. 165273. Altitude 34 mm. Aperture view, × 2. Waldorf asphalt mine (4473). Common in the Pliocene and Pleistocene.

Fig. 12. *Drillia waldorfensis* Arnold. U.S.N.M. 165270. Type. Altitude 18.5 mm. Aperture view of imperfect specimen, × 2. Waldorf asphalt mine (4473). Characteristic of this horizon.

Fig. 13. *Drillia johnsoni* Arnold. U. S. N.M. 165263. Altitude 34 mm. Back view, × 2. Waldorf asphalt mine (4473). Also found fossil at San Pedro.

Fig. 14*a*. *Neverita recluziana* Petit. U.S.N.M. 165323. Altitude 35 mm. Aperture view. Fugler Point asphalt mine near Gary (4475). Also known recent.

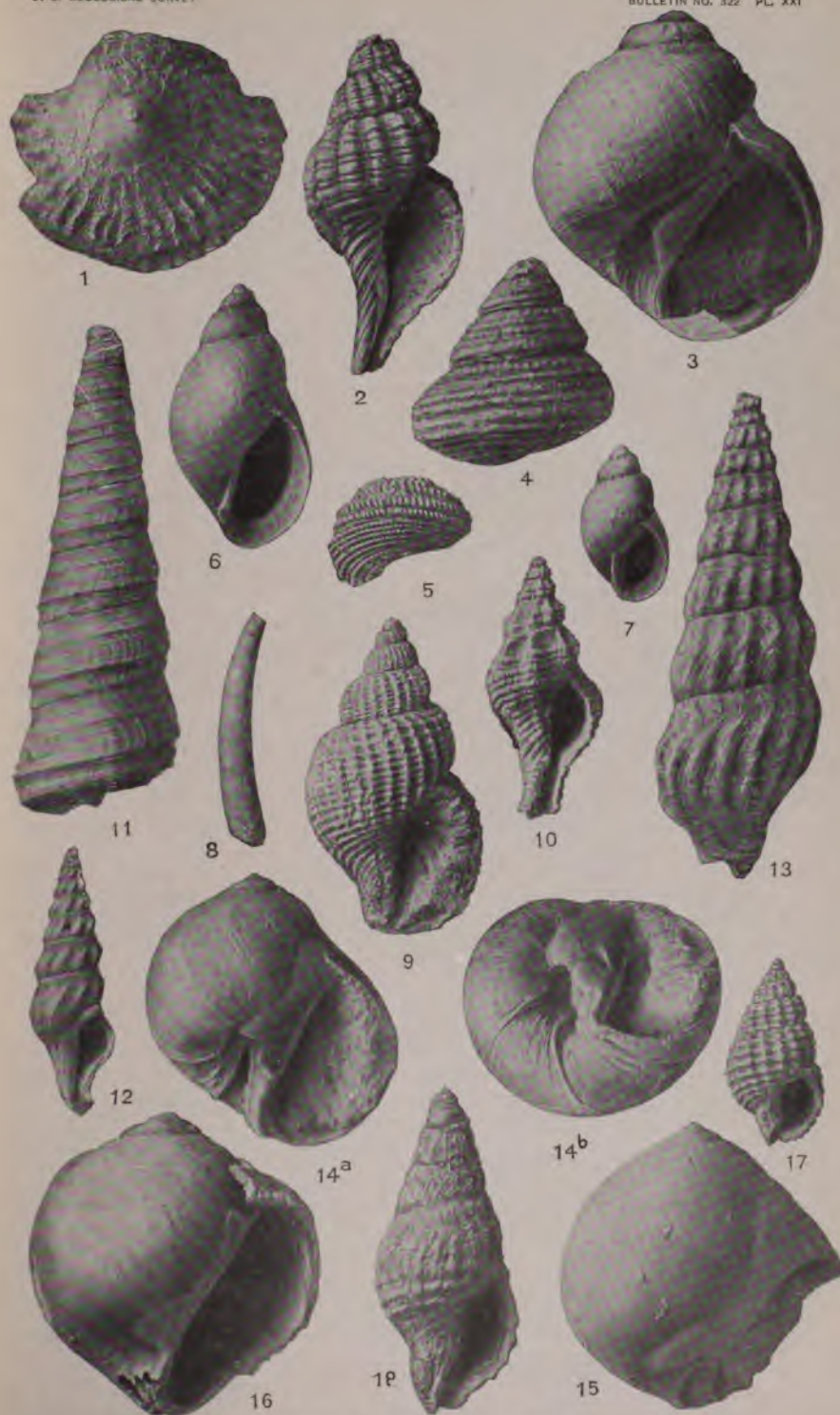
Fig. 14*b*. View of base of same specimen.

Fig. 15. *Neverita recluziana* Petit. U.S.N.M. 165299. Altitude 20 mm. Aperture view, × 2. Fugler Point asphalt mine, near Gary (4475). Also known recent.

Fig. 16. *Natica clausa* Broderip and Sowerby. U.S.N.M. 165269. Altitude 21 mm. Aperture view, × 2. Waldorf asphalt mine (4473). Also known recent.

Fig. 17. *Nassa waldorfensis* Arnold. U.S.N.M. 165272. Type. Altitude 13 mm. Aperture view, × 2. Waldorf asphalt mine (4473). Characteristic of this horizon.

Fig. 18. *Drillia graciosana* Arnold. U.S.N.M. 165309. Type. Altitude 14 mm. Aperture view, × 3. Graciosa Ridge, near Orcutt (4476). Characteristic of this horizon.



FERNANDO (PLIOCENE) GASTEROPODA.

PLATE XXII.

Fernando (Pliocene) Fossils.

(Unless otherwise indicated all figures are natural size.)

Fig. 1*a*. *Pholadidea ovoidea* Gould. U.S.N.M. 165277. Longitude 58 mm. View of valve. Waldorf asphalt mine (4473). Also known recent.

Fig. 1*b*. View of hinge region of both valves.

Fig. 2. *Purpura crispata* Chemintz. U.S.N.M. 165278. Altitude 20 mm. Aperture view. One mile north of Schumann (4474). Also known recent.

Fig. 3*a*. *Leda taphria* Dall. U.S.N.M. 165296. Longitude 10.5 mm. View of exterior, × 3. Fugler Point asphalt mine, near Gary (4475). Also known recent.

Fig. 3*b*. View of hinge region of both valves.

Fig. 4*a*. *Terebratalia occidentalis* Dall. U.S.N.M. 165300. Ventral valve; latitude 30 mm. View of exterior. Fugler Point asphalt mine, near Gary (4475). A variable species. Also known recent.

Fig. 4*b*. View of dorsal valve of same specimen.

Fig. 5. *Macoma nasuta* Conrad. U.S.N.M. 165276. Longitude 47 mm. View of right valve. Waldorf asphalt mine (4473). Also known recent and in Miocene.

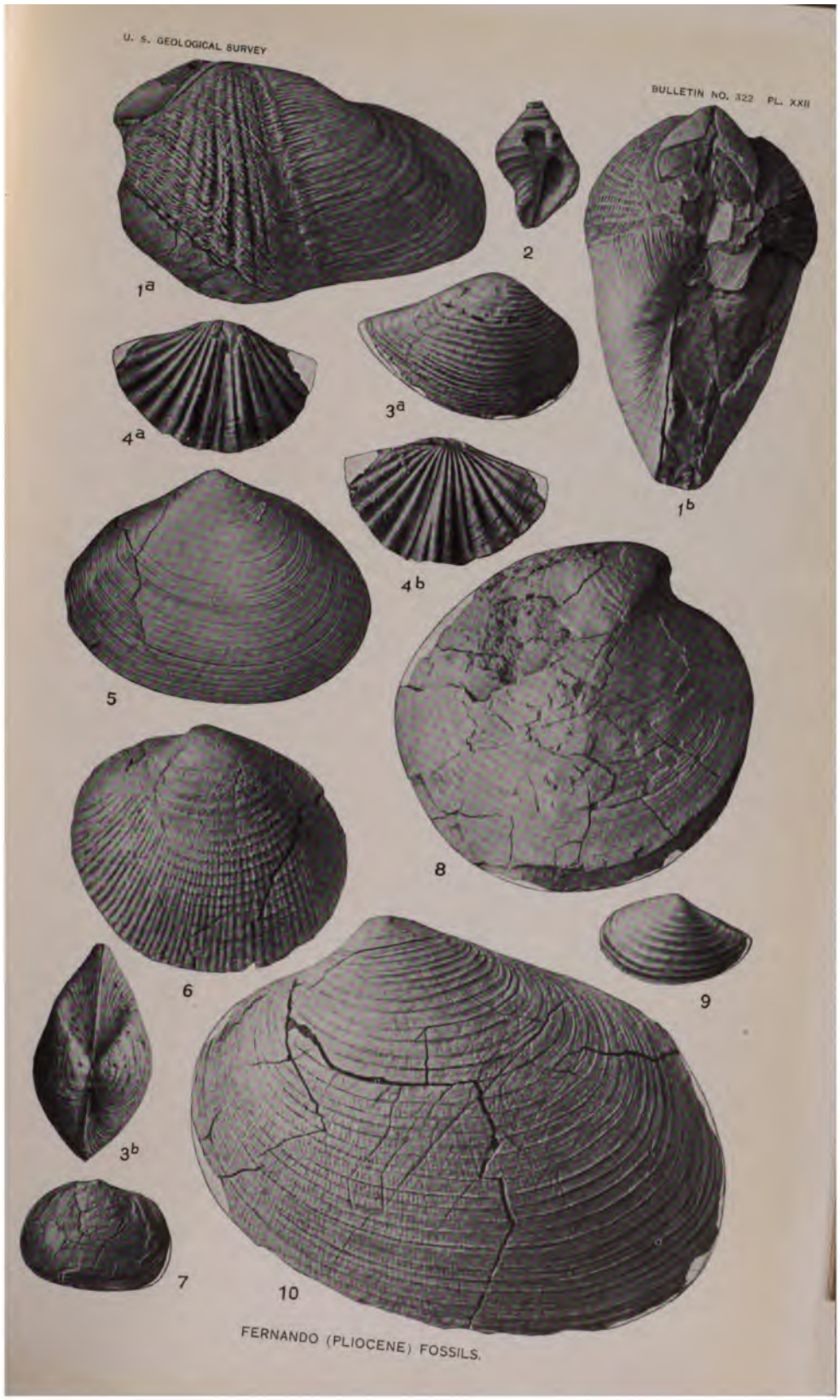
Fig. 6. *Phacoides nuttalli* Conrad var. *antecedens* Arnold. U.S.N.M. 165290. Type. Left valve; longitude 23 mm. View of exterior, × 2. Alcatraz asphalt mine, near Sisquoc (4471). Characteristic of this horizon.

Fig. 7. *Cryptomya ovalis* Conrad. U.S.N.M. 165289. Left valve; longitude 23 mm. Alcatraz asphalt mine, near Sisquoc (4471). Characteristic of this horizon.

Fig. 8. *Dosinia ponderosa* Gray. U.S.N.M. 165295. Right valve; altitude 105 mm. View of exterior, × ½. Alcatraz asphalt mine, near Sisquoc (4471). Also known recent.

Fig. 9. *Leda orcutti* Arnold. U.S.N.M. 165271. Type. Longitude 7 mm. View of exterior, × 3. Waldorf asphalt mine (4473). Characteristic of this horizon.

Fig. 10. *Tapes tenerrima* Carpenter. U.S.N.M. 165293. Left valve; longitude 83 mm. View of exterior. Alcatraz asphalt mine, near Sisquoc (4471). Common in the Pliocene Also known recent.



FERNANDO (PLIOCENE) FOSSILS.

PLATE XXIII.

Fernando (Pliocene) Fossils.

(Unless otherwise indicated all figures are natural size.)

Fig. 1. *Spisula sisquocensis* Arnold. U.S.N.M. 165292. Type. Left valve; longitude 120 mm. View of exterior, × ½. Alcatraz asphalt mine, near Sisquoc (4471). Characteristic of this horizon.

Fig. 2. *Clidiophora punctata* Carpenter. U.S.N.M. 165302. Right valve; longitude 36 mm. View of exterior. Graciosa Ridge, near Orcutt (4476). Also known recent.

Fig. 3. *Clidiophora punctata* Carpenter. U.S.N.M. 165283. Left valve; longitude 35 mm. View of interior. Graciosa Ridge, near Orcutt (4476). Also known recent.

Fig. 4. *Venericardia californica* Dall. U.S.N.M. 165274. Altitude 29 mm. Aperture view. Waldorf asphalt mine (4473). Characteristic of this horizon.

Fig. 5. *Cumingia californica* Conrad. U.S.N.M. 165311. Left valve; longitude 17 mm. View of exterior, × 2. Fugler Point asphalt mine, near Gary (4475). Also known recent.

Fig. 6. *Spisula catilliformis* Conrad var. *alcatrazensis* Arnold. U.S.N.M. 165291. Type. Right valve; longitude 128 mm. View of exterior, × ½. Alcatraz asphalt mine, near Sisquoc (4471). Characteristic of this horizon.

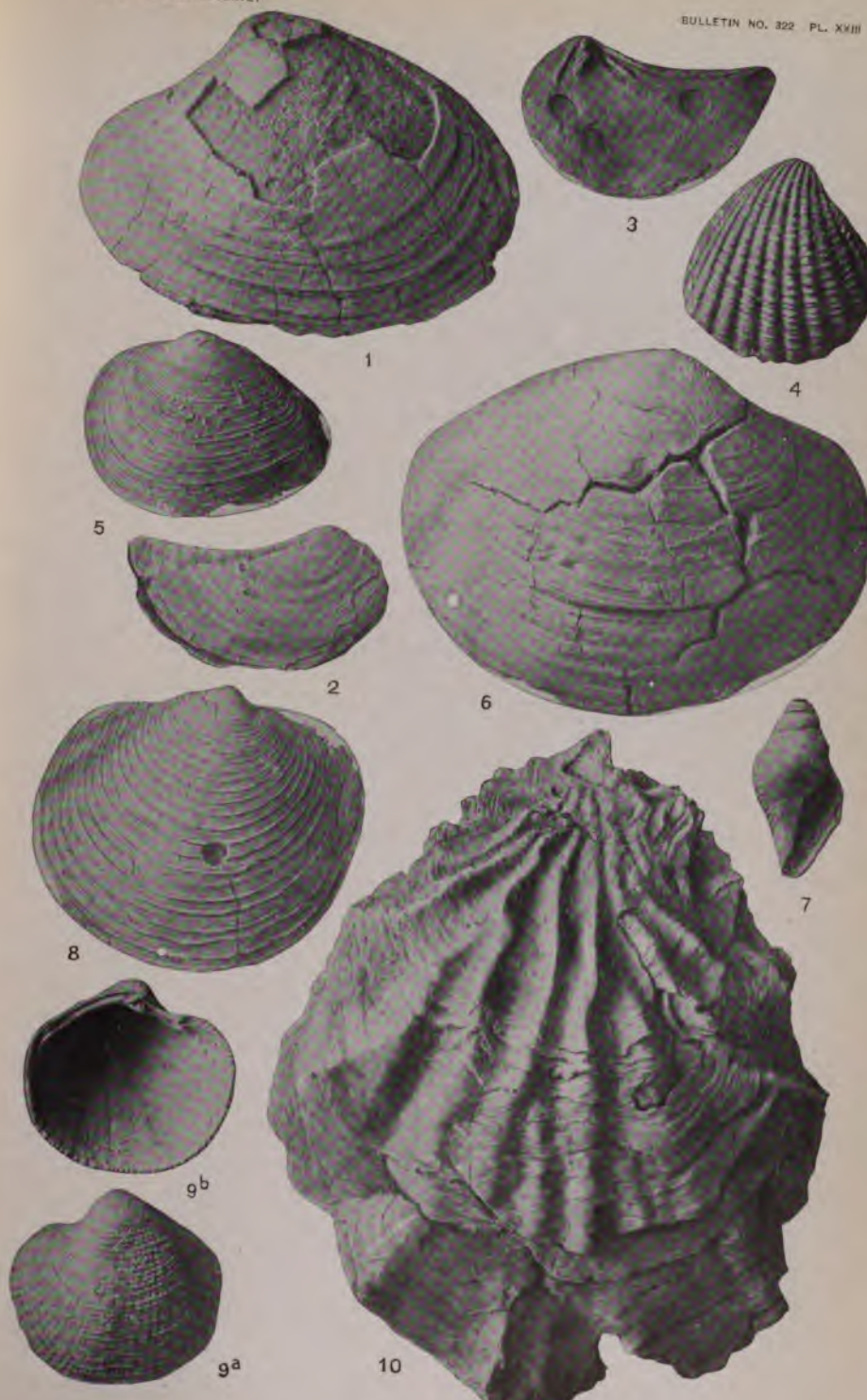
Fig. 7. *Bathytoma carpenteriana* Gabb var. *fernandoana* Arnold. U.S.N.M. 165303. Type. Altitude 24 mm. Aperture view. Graciosa Ridge, near Orcutt (4476). Characteristic of this horizon.

Fig. 8. *Phacoides annulatus* Reeve. U.S.N.M. 165286. Right valve; longitude 45 mm. View of exterior. One mile north of Schumann (4474). Common in the Fernando and also found recent.

Fig. 9*a*. *Phacoides intensus* Dall. U.S.N.M. 165260. Left valve; altitude 6.5 mm. View of exterior, × 4. Waldorf asphalt mine (4473). Found also in same horizon at San Diego.

Fig. 9*b*. View of interior of same specimen, × 4.

Fig. 10. *Ostrea veatchii* Gabb. U.S.N.M. 165282. Left valve; altitude 96 mm. View of exterior. One mile north of Schumann (4474). Characteristic of this horizon.



FERNANDO (PLIOCENE) FOSSILS.

PLATE XXIV.

Fernando (Pliocene) Fossils.

(Unless otherwise indicated all figures are natural size.)

Fig. 1. *Crepidula princeps* Conrad. U.S.N.M. 165268. Longitude 76 mm. Side view. Waldorf asphalt mine (4473). Known only in the fossil state, and found in Santa Barbara County only in the Fernando formation, although it is known from the lower Miocene farther north.

Fig. 2. *Crepidula princeps* Conrad. U.S.N.M. 165315. Longitude 106 mm. View of interior, showing deck. Packards Hill, Santa Barbara.

Fig. 3. *Astyris richthofeni* Gabb. U.S.N.M. 165266. Altitude 14 mm. Aperture view, × 2. Waldorf asphalt mine (4473). So far known only as fossil.

Fig. 4. *Nassa californiana* Conrad. U.S.N.M. 165304. Altitude 30 mm. Aperture view. Graciosa Ridge, near Orcutt (4477). Characteristic of this horizon in the Santa Maria district.

Fig. 5. *Arca trilineata* Conrad. U.S.N.M. 165301. Left valve; longitude 46 mm. View of exterior. Fugler Point asphalt mine, near Gary (4475). Common in the Fernando and equivalent formations and also found in the Monterey.

Fig. 6. *Echinarachnius ashleyi* Merriam. U.S.N.M. 165259. Maximum diameter 69 mm. View from above. Graciosa Ridge, near Orcutt (4469).

Fig. 7. *Echinarachnius ashleyi* Merriam. U.S.N.M. 165259. Maximum diameter 47 mm. View from below. Same locality as fig. 6.

Fig. 8. *Echinarachnius excentricus* Eschscholtz var. U.S.N.M 165285. Maximum diameter 41 mm. View of top. One mile north of Schumann (4474). This variety is probably characteristic of this horizon.

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FERNANDO (PLIOCENE) FOSSILS.

PLATE XXV.

FERNANDO (PLIOCENE) PECTENS.

(Unless otherwise indicated all figures are two-thirds natural size.)

FIG. 1*a*. *Pecten* (*Pecten*) *stearnsii* Dall. U.S.N.M. 148008. Right valve; altitude 87 mm. View of exterior. San Diego formation (Pliocene), Pacific Beach, San Diego County, Cal. Common in the Fernando formation of southern California.

FIG. 1*b*. Same specimen as fig. 1*a*. Exterior of left valve.

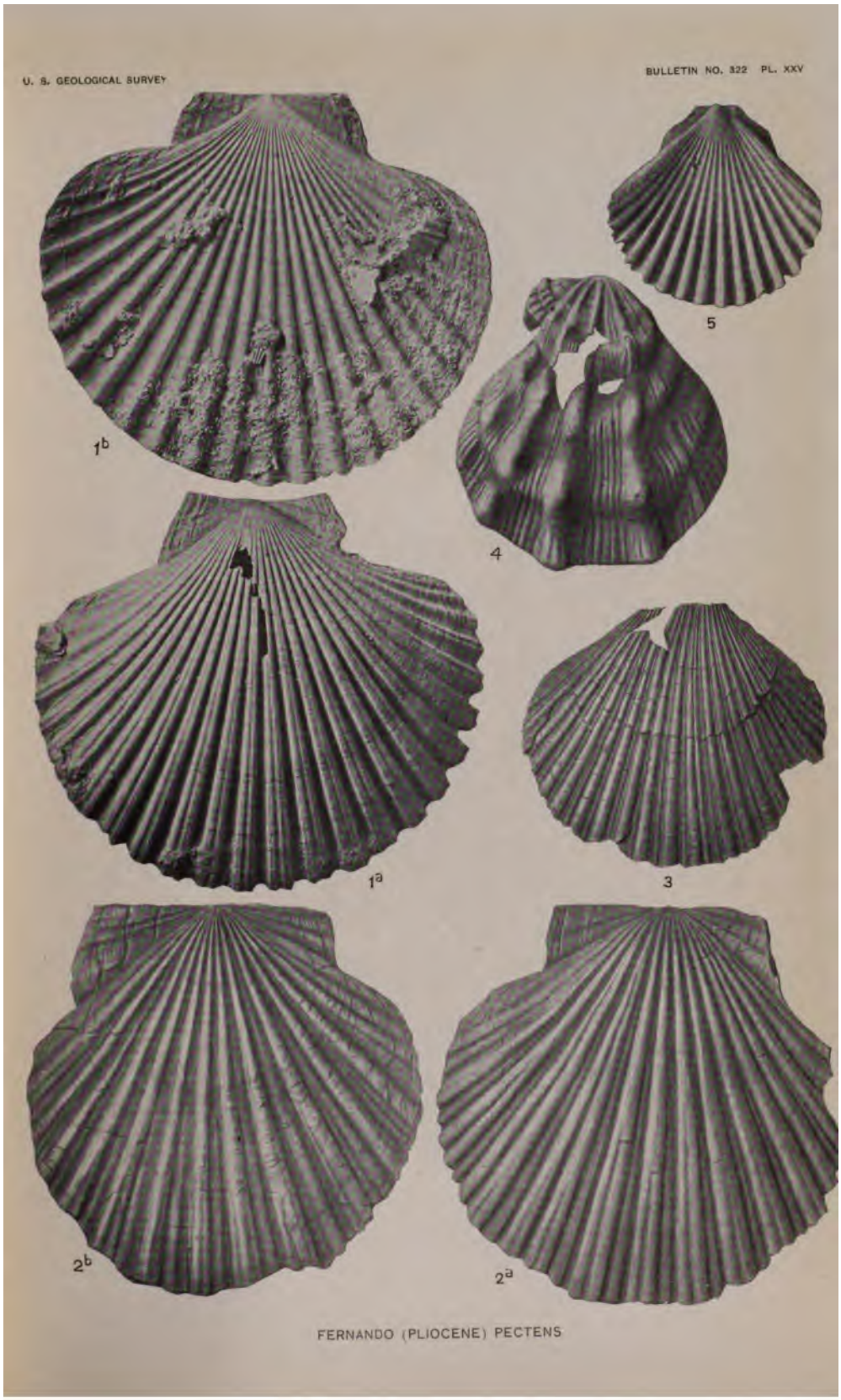
FIG. 2*a*. *Pecten* (*Patinopecten*) *oweni* Arnold. Collection of University of California. Type. Right valve, anterior ear slightly broken; altitude 85 mm. View of exterior. Foxen's ranch. Characteristic of this horizon.

FIG. 2*b*. Same specimen as fig. 2*a*. Exterior of left valve.

FIG. 3. *Pecten* (*Chlamys*) *lawsoni* Arnold. Collection of California Academy of Science. Type. Right valve (umbo and ears missing); longitude 65 mm. View of exterior. One mile north of Schumann. Characteristic of this horizon.

FIG. 4. *Pecten* (*Chlamys*) *wattsi* Arnold. Collection of California Academy of Science. Type. Slightly imperfect left valve; altitude 66 mm. View of exterior. Lower Pliocene, Kreyenhagen's ranch, Fresno County. Common in the Fernando of southern California.

FIG. 5. *Pecten hemphilli* Dall. U.S.N.M. 165280. Left valve; altitude 22.50 mm. View of exterior, $\times 1\frac{2}{3}$. One mile north of Schumann (4474). Characteristic of this horizon.



FERNANDO (PLIOCENE) PECTENS

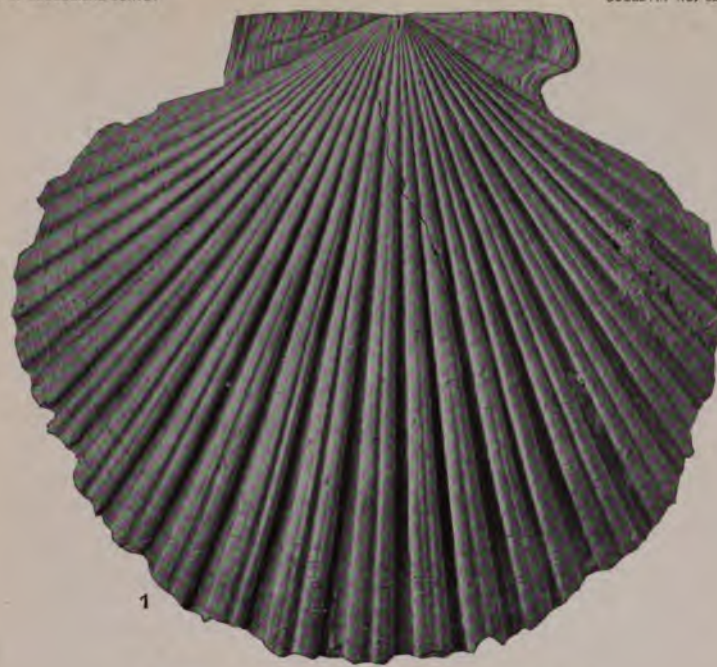
PLATE XXVI.

FERNANDO (PLIOCENE) PECTEN.

(Unless otherwise indicated all figures are two-thirds natural size.)

FIG. 1. *Pecten* (*Patinopecten*) *healeyi* Arnold. U.S.N.M. 148012. Holotype. Right valve; altitude 121 mm. View of exterior. San Diego formation (Pliocene), San Diego County, Cal. Characteristic of the Fernando formation throughout the Coast Range.

FIG. 2. *Pecten* (*Patinopecten*) *healeyi* Arnold. U.S.N.M. 154162. Paratype. Left valve; altitude 141 mm. View of exterior. San Diego formation (Pliocene), Pacific Beach, San Diego County, Cal.



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FERNANDO (PLIOCENE) PECTENS.

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[Bulletin No. 322.]

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EXPERIMENTAL WORK

CONDUCTED IN THE

CHEMICAL LABORATORY

OF THE

UNITED STATES FUEL-TESTING PLANT AT ST. LOUIS, MO.

JANUARY 1, 1905, TO JULY 31, 1906

BY

N. W. LORD

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EXPERIMENTAL WORK CONDUCTED IN THE CHEMICAL LABORATORY OF THE UNITED STATES FUEL-TESTING PLANT, ST. LOUIS, JANUARY 1, 1905, TO JULY 31, 1906.

By N. W. Lord.

INTRODUCTION.

The experimental work reported upon herein was performed at the laboratory of the United States fuel-testing plant on the grounds of the Louisiana Purchase Exposition at St. Louis, Mo., between January 1, 1905, and July 31, 1906, and was undertaken for the purpose of checking the results obtained in the routine work of the laboratory, improving the methods of working, and investigating the chemical and physical properties of coal. The laboratory having been designed primarily for the analysis of the coal samples sent to the fuel-testing plant, as well as those taken in connection with the regular testing operations of the boiler, gas-producer, and other divisions of the plant, only a very small proportion of the time of the force was available for experimental work outside of the regular routine.

From the nature of such work it was not possible to separate the results obtained in 1905 from those obtained in 1906, especially as many of the experiments, such as those on the alteration of coal, involved a long time and were started in 1905 and continued to the middle of 1906. This report therefore covers all such work up to its completion in July, 1906.

The complete history of the coals used in these experiments is not given, the samples being usually referred to by their laboratory numbers only, as such information is generally not necessary and does not affect the interpretation of the results obtained in the experiments. Fuller information as to any particular sample may be found in the published reports of the fuel-testing plant for 1905 and 1906.

In the following pages the results of each line of experimental work are given under a special heading indicating the object of the investigation.

While many of the investigations can only be regarded as preliminary, it is believed that the mass of the results will be of value in shedding light on some matters of general interest.

ACCURACY OF METHOD OF TAKING CAR SAMPLES.

The regular method of taking car samples has been fully described under "Sampling" in Professional Paper No. 48, page 175. To check the accuracy of this method, check samples on two cars of coal rather high in moisture, ash, and sulphur were taken at the same time that the regular sample was taken, by opening a gate in the conveyor runway every four or five minutes, and thereby allowing the contents of one or two buckets passing at that time to be emptied into a small bin. In this way a sample of 1,200 to 1,500 pounds was taken during the unloading of the car. This sample was then put through a small crusher, crushed to ½-inch size, and resampled at the conveyor buckets, and a sample was sent to the chemical laboratory for analysis. In the following table the Indiana coal was a run-of-mine coal, and the amount sampled was approximately 20 tons; and the Ohio coal was a run-of-mine coal, and the amount sampled was approximately 26 tons.

Moisture, ash, and sulphur determinations from samples of two cars of run-of-mine coal.

Constituent.	Indiana coal.		Ohio coal.	
	Regular sample.	Check sample.	Regular sample.	Check sample.
Moisture	10.80	10.47	9.01	9.43
Ash	12.62	12.92	11.33	11.59
Sulphur	4.39	4.43	4.02	4.02

For coals containing such high percentages of ash and sulphur the agreement between these independently taken samples is satisfactory. It indicates, so far as the sampling is concerned, that the analytical work may be taken as closely representing the average of the carload.

MOISTURE LOSS IN COARSE SAMPLES FROM STANDING IN COVERED METAL PAILS.

The large samples from the fuel-testing plant were sent to the laboratory in closed metal pails, and some of them were allowed to stand in the pail several hours, or occasionally over night, before sampling. To see if any considerable amount of moisture might be lost in this way, a portion of the wet sample from the washery (Pennsylvania No. 9 coal) was taken as the most favorable case, and allowed to stand for five days in the closed pail in the laboratory before sampling. The average temperature for the five days was 18° C., and the atmospheric humidity 60 per cent. The percentages of moisture determined by

analysis of this sample, and analysis of the portion of the sample reduced at once, are as follows:

	Per cent.
Portion sampled at once	5.07
Portion sampled after standing five days	4.58
Loss by standing	.49

These coals dry down to about 1 per cent moisture, so that the loosely held and surface moisture amounted to about 4 per cent. From this experiment the moisture loss which occurs during the short time that the sample usually is allowed to stand in the laboratory before sampling would appear to be unimportant.

INVESTIGATION OF MOISTURE LOSSES DURING SAMPLING.

In preparing the samples for these tests the coarse sample (40 to 50 pounds in weight), when received at the laboratory, was divided by quartering. One portion of 500 grams was at once ground without air drying in the ball mill. Another portion of about 5 to 10 pounds was air dried in the usual way before the final pulverization. The results (reduced to sample as received) in moisture and ash for the two portions are as follows:

Moisture and ash determinations on air-dried samples and fresh samples of coal.

Designation of sample.	Regular sample (air dried).		Fresh sample (not air dried).	
	Moisture.	Ash.	Moisture.	Ash.
Illinois	13.54	10.74	[a] 9.36	11.37
	13.72	10.32	11.92	10.40
Texas No. 4	33.85	7.30	33.00	7.65
Arkansas No. 8	5.19	14.01	3.58	14.16
Indiana No. 12	10.57	11.65	9.95	11.98
Illinois No. 23 B	15.68	15.59	14.78	16.11
Illinois No. 23 A	13.47	11.53	12.43	11.63
Missouri No. 6	13.80	11.74	12.58	11.15
Illinois No. 22 A	11.91	13.01	11.58	12.57

[a] This sample was ground very fine in ball mill, which probably accounts for the loss being so large.

The results obtained for moisture from the original samples that were ground down without preliminary air drying are without exception decidedly lower than the results obtained from the regularly prepared air-dried samples when calculated to the sample as received, the greatest difference being over 4 per cent and the average difference over 1½ per cent. Furthermore, the fine sample, after being ground without previous air drying, as shown by experiments (see pp. 13–17), gives up moisture so readily as to indicate that a large additional loss during the handling and weighing of the sample in the laboratory is almost certain. The consequent errors due to moisture losses are liable to be so large as to affect very seriously the accuracy of the results obtained.

DETERMINATION OF ERRORS DUE TO ABRASION OF PEBBLES USED IN BALL MILL.

During the Louisiana Purchase Exposition the final pulverization of the samples was done on a bucking board. In the work done during 1905 the final grinding of the sample was done in closed jars in the ball mill, quartz pebbles being used.

In order to determine whether there was danger of materially increasing the ash contents of the samples from chipping and abrasion of the pebbles used in grinding, these pebbles were carefully weighed at intervals and the amount of loss determined. The weight of the sample ground each time in the ball mill is approximately 500 grams, and the abrasion of the pebbles (calculated as percentage of the weight of the samples ground) was also carefully determined. The results on three weighed lots of pebbles are as follows:

Losses of weight in three lots of quartz pebbles before and after grinding in the ball mill.

Lot.	Total weight of samples ground.	Weight of pebbles.		Loss by abrasion.	
		Before grinding	After grinding.	Actual.	Ratio to coal ground.
	Grams.	*Grams.*	*Grams.*	*Grams.*	*Per cent.*
No. 1 (250 samples ground)	125,000	4,118.6	4,113 1	5.5	0.004
No. 2 (230 samples ground)	115,000	3,502.9	3,499.4	3.5	.003
No. 3 (245 samples ground)	122,500	4,273.2	4,268.3	4.9	.004

These results show that as far as the fine pulverization of the coal is concerned, there is little or no danger of increasing the ash content of the sample appreciably by using quartz pebbles as the grinding medium. The pebbles used show no tendency to chip, as the loss between weighings taken before and after 25 to 50 samples were ground in no case amounted to over 1 gram, the abrasion being in all cases approximately proportional to the weight of samples ground.

COMPARISON OF RESULTS OF AIR DRYING IN THE SPECIAL OVEN AND BY EXPOSURE.

The samples as received at the laboratory were dried to approximately an air-dry condition, before their final pulverization, in an oven especially designed for this purpose. To find out how nearly this method of drying approximates air drying under ordinary conditions, the following tests were made:

The loss in weight of samples of different coals allowed to air dry under observed conditions of temperature and humidity was determined by allowing portions of the coarse samples spread on trays to remain exposed to the air of the laboratory for periods of time ranging from seven to twenty days. The samples were weighed from time

to time and the drying continued until the weight remained almost constant. The air-drying loss of these samples and the loss in weight of the corresponding regular samples dried in the dryer, with the amount of moisture remaining in the dryer samples, are tabulated below. In most of the samples the dryer loss is not widely different from the loss on the air-dry sample. Special exceptions are Nos. 1960 (Indiana No. 9 B) and 1390 (Wyoming No. 6), on which samples the dryer-sample loss is decidedly larger than that on the samples dried by exposure to the air of the laboratory. The samples dried during the summer months were exposed to air of a high average humidity (60 per cent), as the temperature and humidity of the laboratory were approximately that of the outdoor air for that period. The samples dried during the winter months were exposed to air of low average humidity (30 per cent), as the temperature of the laboratory was decidedly higher than that of the outdoor air, with approximately the same absolute amount of moisture present in the laboratory and in the outdoor air. The humidity of the warmer laboratory air is consequently low. The percentage of moisture remaining in the samples dried by exposure to the air of the laboratory was determined by adding or subtracting (according to whether it was plus or minus) the difference between the loss in the dryer and the loss in the exposed sample to the moisture remaining in the "dryer sample," as given in the table below:

Results of tests for moisture in samples of coal.

Sample of coal.		Moisture in sample.					Time of drying by exposure	Air of laboratory.	
Laboratory number.	Field number.	As received.	Loss on coarse sample, as dried— By exposure.	Loss on coarse sample, as dried— In dryer.	After drying— By exposure (calculated).	After drying— In dryer.		Temperature.	Humidity.
		Per ct.	*Per ct.*	*Per ct.*	*Per ct.*	*Per ct.*	*Days.*	*° C.*	*Per ct.*
3294	New Mexico No. 5	2.72	1.60	1.40	1.14	1.34	17	25	63
3265	Alabama No. 3	2.72	0.30	1.20	2.44	1.54	13	25	64
3308	New Mexico No. 3	2.75	1.40	1.40	1.37	1.37	19	25	63
3331	New Mexico No. 4 A	2.78	0.40	1.40	2.40	1.40	14	24	62
3406	Indian Territory No. 2 B	2.81	0.60	1.40	2.23	1.43	16	26	64
2626	West Virginia No. 20	2.89	1.98	1.90	0.93	1.01	16	21	26
3315	New Mexico No. 4 B	3.38	1.60	1.70	1.81	1.71	18	25	62
3295	New Mexico No. 3 A	3.45	1.50	2.00	1.98	1.48	17	25	63
2332	West Virginia No. 17	3.46	2.07	2.50	1.43	1.00	11	21	47
2572	West Virginia No. 21	3.57	2.24	2.10	1.36	1.50	12	19	28
2420	Virginia No. 1	4.06	2.59	2.40	1.51	1.70	9	25	27
3307	New Mexico No. 3 B	4.36	2.20	3.00	2.20	1.40	19	25	63
2528	Kentucky No. 5	4.36	1.77	2.80	2.63	1.60	10	24	31
2264	West Virginia No. 16 B	5.57	3.89	4.40	1.73	1.22	11	18	57
3286	Utah No. 1	5.83	2.30	2.10	3.61	3.81	17	25	63
3405	Indian Territory No. 2 B	6.27	4.20	4.90	2.14	1.44	16	26	64
1761	Illinois No. 15	9.95	3.62	4.20	6.58	6.00	18	27	64
1876	Indiana No. 6	10.47	6.02	6.30	4.73	4.45	14	27	64
3225	Wyoming No. 5	11.44	4.10	3.70	7.64	8.04	21	25	53
2896	Illinois No. 22 B	13.03	9.74	11.20	3.52	2.06	8	23	35
1960	Indiana No. 9 B	13.53	7.13	10.70	6.74	3.17	18	27	67
2686	Washington No. 1 B	14.30	8.12	9.60	6.68	5.20	9	22	28
2731	Illinois No. 20	14.68	11.80	12.40	3.20	2.60	11	23	34
2803	Illinois No. 23 B	15.68	13.98	13.20	2.08	2.86	10	24	31
3390	Wyoming No. 6	19.00	7.50	11.30	12.48	8.68	16	27	64

These values show that on most of the coals tested drying in the drier brought the sample to approximately an air-dry condition. No effort had been made to do more than this, as the primary object in the air drying is to get the sample into such a condition that the fine sample will not be subject to large moisture changes during subsequent handling in the laboratory. The air drying, therefore, is not to be understood as being a rigidly fixed determination; but it has been found that the values obtained as a rule are within a sufficiently definite range to give this determination some importance as showing the effect of standing and exposure on the percentage of moisture in the coal. This matter is of considerable commercial importance, since, so far as the moisture content is concerned, coals having a large air-drying loss are obviously much more affected than coals having a small air-drying loss. It further has appeared that the amount of residual moisture in the air-dried sample prepared under the described conditions usually lies within a range which is somewhat characteristic of different kinds of coal.

The foregoing table shows this residual moisture to be about 1 per cent in the West Virginia coals, 3 to 6 per cent in the Illinois and Indiana coals, and from 10 to 12 per cent in the Wyoming samples.

COMPARISON OF RESULTS FOR MOISTURE OBTAINED FROM SAMPLES PULVERIZED BY VARIOUS METHODS.

The possibility of moisture loss during grinding on a bucking board has already been referred to. In order to obtain more data upon different coals and under observed conditions of temperature and humidity, duplicate portions of a number of samples were ground down upon the bucking board and the moisture determinations made upon these portions. At the same time portions of the coal which had only passed the 1 10-inch mesh sieve in the process of sampling were reserved as samples for determining moisture in the coal at this size. The moisture was determined in these samples by drying 5 grams for one hour in the air bath, instead of 1 gram as in the regular determination. The moisture results on these samples and the results upon the regular samples ground down in the ball mill, together with the temperature and humidity conditions of the laboratory at the time of sampling, are given in the following table:

Results for moisture from coal samples variously pulverized.

Sample of coal.		Moisture in sample from—			Air of laboratory.	
Laboratory number.	Field number.	Bucking board.	Ball mill.	1/16-inch mesh sieve.	Temperature.	Humidity.
		Per cent.	*Per cent.*	*Per cent.*	*° C.*	*Per cent.*
3255	Alabama No. 3	1.43	1.54	1.43	29	66
2689	Arkansas No. 1 B	0.89	0.85	0.69	23	30
2688	Arkansas No. 7 A, 7 B	0.62	0.60	0.50	23	30
2722	Arkansas No. 7 B	0.94	1.05	0.87	23	30
2744	Arkansas No. 8	0.75	0.83	0.81	28	37
2690	Arkansas No. 9	1.22	1.11	1.03	23	30
1835	Brazil	5.40	4.95	4.80	30	67
1680	California No. 1	.....	9.05	[a] 7.28	29	60
1699	.....do	.....	8.89	7.42	22	61
1702	Illinois No. 6 B	.....	4.17	4.22	27	52
1780	Illinois No. 7 D	6.82	7.60	7.48	24	70
1635	Illinois No. 9 A	4.92	4.99	5.36	20	59
1639	Illinois No. 9 B	.....	4.03	3.73	25	39
1638	.....do	10.58	12.34	12.35	21	60
1648	Illinois No. 10	.....	2.79	2.94	28	37
1653	Illinois No. 11 A	.....	2.98	2.59	24	55
1654	.....do	.....	3.11	2.82	24	55
1717	Illinois No. 11 C	2.97	2.42	2.39	27	64
1802	Illinois No. 11 D	6.06	6.30	6.01	26	64
1786	Illinois No. 13	4.22	3.89	3.68	25	63
1740	Illinois No. 14	5.24	5.19	5.29	35	53
1761	Illinois No. 15	6.10	6.00	5.84	25	77
1820	Illinois No. 16	4.74	4.61	4.46	28	72
1926	Illinois No. 19 A	6.46	6.39	6.20	31	56
3447	Illinois No. 19 C	5.43	6.01	5.57	33	49
3448	Illinois No. 19 D	3.98	3.87	3.95	33	49
3451	.....do	4.83	5.27	4.96	33	49
2731	Illinois No. 20	2.89	2.60	2.57	25	39
2852	Illinois No. 21	4.42	5.74	5.61	23	30
2905	Illinois No. 22 A	4.45	6.39	6.39	24	20
2896	Illinois No. 22 B	2.14	2.06	1.86	24	20
2803	Illinois No. 23	2.47	2.86	2.65	24	31
2819	Illinois No. 23 A	2.05	2.23	1.93	22	28
1941	Indiana No. 3	5.19	5.12	4.93	29	60
1844	Indiana No. 4	4.04	3.58	3.42	28	72
1859	Indiana No. 5	5.62	5.21	5.60	21	68
1875	Indiana No. 6	5.76	5.91	5.71	21	60
1881	Indiana No. 7 A	5.60	5.50	5.46	27	71
2037	Indiana No. 8	3.99	5.19	5.16	23	69
1960	Indiana No. 9 B	3.30	3.17	3.04	28	72
1979	Indiana No. 10	2.98	2.85	2.62	31	63
2087	Indiana No. 11	7.92	8.49	8.52	22	75
2759	Indiana No. 12	3.45	4.45	4.29	19	35
3405	Indian Territory No. 2 B	1.70	1.44	1.34	31	63
3406	.....do	1.65	1.43	1.38	31	63
2843	Kansas No. 6	1.71	2.09	1.83	24	25
2528	Kentucky No. 5	1.66	1.60	1.34	23	37
2592	Kentucky No. 6	2.66	2.99	2.80	22	28
2274	Maryland No. 1	1.12	0.94	0.99	24	70
2865	Missouri No. 5	1.59	1.71	1.55	24	25
2904	Missouri No. 6	1.63	2.49	2.62	24	31
2937	Missouri No. 7	5.25	7.41	7.45	21	33
2942	.....do	2.54	2.48	2.28	20	37
3295	New Mexico No. 3	1.03	1.48	1.34	30	57
3307	New Mexico No. 3 B	1.43	1.40	1.38	28	65
3308	.....do	1.33	1.37	1.33	25	65
3315	New Mexico No. 4	1.56	1.71	1.64	28	43
3331	New Mexico No. 4 A	1.54	1.40	1.14	31	47
3294	New Mexico No. 5	1.36	1.34	1.24	30	67
2071	Ohio No. 1	3.40	2.96	2.65	21	75
2109	Ohio No. 2	5.60	5.60	5.57	27	72
2144	Ohio No. 3	5.43	6.24	6.15	18	73
2083	Ohio No. 4	2.56	2.16	1.94	24	85
2062	Ohio No. 5	2.25	1.99	1.84	18	73
2310	Ohio No. 9 A	2.55	2.47	2.56	19	66
2311	Ohio No. 9 B	2.78	2.65	2.37	19	66
2115	Pennsylvania No. 5 A	1.82	1.77	1.77	24	76
2068	Pennsylvania No. 5 B	1.57	1.47	1.38	21	75
2152	Pennsylvania No. 8	0.77	0.64	0.87	31	53
3102	Tennessee No. 6	1.27	1.02	1.02	24	31
3127	Tennessee No. 8 A	1.01	1.05	0.98	29	38
3128	Tennessee No. 8 B	0.92	1.14	1.02	25	33
2734	Texas No. 3	9.06	9.88	8.48	23	24
2717	Texas No. 4	8.63	9.76	8.67	21	26
3199	Utah No. 1	2.23	2.34	2.32	24	31
2420	Virginia No. 1 A	1.60	1.70	1.60	24	25

[a] Heated two hours, moisture = 7.86; heated three hours, moisture = 8.03.

Results for moisture from coal samples variously pulverized—Continued.

Sample of coal.		Moisture in sample from—			Air of laboratory.	
Laboratory number.	Field number.	Bucking board.	Ball mill.	1/10-inch mesh sieve.	Temperature.	Humidity.
		Per cent.	*Per cent.*	*Per cent.*	*° C.*	*Per cent.*
2358	Virginia No. 4	2.35	2.40	2.28	28	26
2687	Washington No. 1 A	5.38	5.98	5.85	20	24
2686	Washington No. 1 B	4.55	5.20	4.65	20	24
2250	West Virginia No. 4 B	1.45	1.35	1.19	23	69
2028	West Virginia No. 13	1.10	1.17	1.15	23	69
2004	West Virginia No. 14	2.00	2.05	2.05	34	50
2332	West Virginia No. 17	1.15	1.00	1.00	20	59
2527	West Virginia No. 18	1.29	1.28	1.13	23	37
2549	West Virginia No. 19	0.65	0.68	0.65	22	22
2572	West Virginia No. 21	1.43	1.50	1.44	20	24
2131	Wyoming No. 2 B	4.57	4.65	4.48	23	85
3213	Wyoming No. 5	5.61	6.00	6.04	31	46
3390	Wyoming No. 6	8.90	8.68	8.24	32	55

The results for moisture obtained on the 5-gram portion of the coarse sample, as a rule, run from 0.1 to 0.2 per cent lower than the moisture value as determined upon the sample ground in the ball mill. In a few cases the moisture result on the coarse sample is somewhat higher than the result on the ball-mill sample, while in a few other cases, noticeably the lignite samples from California and Texas, the moisture result on the coarse sample is decidedly lower. This result, as shown by tests on sample 1680, California No. 1, may be ascribed to the fact that the moisture in a coarse sample of lignite is very incompletely expelled by one hour's heating. An additional two hours of heating upon this sample resulted in an increased moisture value of over 0.7 per cent. As a method applied to any and all coals, the determination of the moisture in the fine sample appears to be preferable to the determination in the coarse sample. The results obtained for moisture upon the samples ground down on the bucking board, as compared with the results obtained on the samples ground down in the ball mill, show that the bucking-board samples may either gain or lose moisture, depending on the thoroughness of the preliminary drying of the coarse samples and the humidity of the air in the laboratory at the time of sampling. For Illinois coals previously dried down to a moisture content of about 5 or 6 per cent, the bucking-board sample took up moisture during grinding when the humidity was high (70 per cent or more). On the other hand, with low humidity (20 to 30 per cent), the moisture loss during grinding was considerable, and a careful study of the results obtained upon the bucking-board sample, as compared with the results on the ball-mill sample, taken in connection with the humidity changes, shows that any success in attempting to work the sample down on the bucking board without danger of moisture changes is practically impossible of realization, and that the sample ground down on the bucking board can not be in any case regarded as entirely satisfactory on account of the danger of moisture changes during the sampling. The experiments reported under the

following heading, showing the rapid changes in moisture in coal samples when spread on the watch glass, indicate that there is probably a slight gain or loss of moisture in the ball-mill sample even during the short time that this sample is exposed to air during sampling, and that this change may be considerable if the coarse sample be very far from an air-dried condition before being ground down. The grinding down of samples in the ball mill can not, therefore, be considered as perfectly satisfactory in so far as moisture changes are concerned; but this method of grinding, in connection with the preliminary drying of the coarse sample, is much more satisfactory and reliable than any other practical method that has been devised of which the writer has any knowledge. Therefore it appears that the handling of samples in this manner, as compared with the practice in most general use, is an important step in the direction of securing a sample for analysis with a minimum amount of unaccounted-for changes in moisture.

CHANGES IN MOISTURE CONTENT OF FINE SAMPLES OF COAL UNDER MODIFIED CONDITIONS.

That coal in a fine condition changes rapidly in moisture content is well known. In order to obtain definite information as to the rate of this change a number of tests were made on coals under different conditions. The first selection for testing was a fine sample (No. 1638 C) of undried Illinois coal, containing 12.4 per cent moisture. One gram of this sample was spread out on a 4-inch watch glass and weighed at intervals, a record of the temperature and humidity being taken at the time of the different weighings. A second series of tests was also made on a 10-gram portion of this sample spread upon a 4-inch watch glass. A third series of tests was made upon another portion of this sample (17.2 grams) by allowing it to stand in an open, wide-mouthed 2-ounce bottle and weighing at intervals. The results for these three series of tests are as follows:

Changes in moisture content of sample (No. 1638 C) of undried Illinois coal.

FIRST SERIES—1 GRAM ON 4-INCH WATCH GLASS.

Time interval between weighings.	Loss or gain in weight.		Air of laboratory.	
			Temperature.	Humidity.
	Grams.	*Per cent.*	° *C.*	*Per cent.*
5 minutes	−0.0202	− 2.02	22	21
5 minutes	− .0075	− .75	.....	.....
15 minutes	− .0090	− .90	.....	.....
1½ hours	− .0110	− 1.10	25	50
24 hours	− .0350	− 3.50	24	36
24 hours	− .0120	− 1.20	28	36
25 hours	+ .0140	+ 1.40	25	63
42 hours	+ .0060	+ .60	18	64
104 hours	− .0127	− 1.27	27	35
15 days	+ .0007	+ .07	32	41
48 days	− .0175	− 1.75	32	55
Total loss in 72 days	.....	10.42	.....	.....

Changes in moisture content of sample (No. 1638 C) of undried Illinois coal—Continued.

SECOND SERIES—10 GRAMS ON 4-INCH WATCH GLASS.

Time interval between weighings.	Loss or gain in weight.		Air of laboratory.	
			Temperature.	Humidity.
	Grams.	*Per cent.*	° *C.*	*Per cent.*
5 minutes	−0.0280	−0.28	25	50
5 minutes	− .0380	− .38	.....	.....
15 minutes	− .0605	− .61	.....	.....
1½ hours	− .1965	−1.96	25	43
21 hours	− .2535	−2.54	24	36
24 hours	− .2140	−2.14	28	35
25 hours	+ .0575	+ .58	25	63
42 hours	+ .0130	+ .13	18	64
104 hours	− .0518	− .52	27	35
15 days	− .0622	− .62	32	41
48 days	− .0725	− .72	32	55
Total loss in 72 days	.....	9.06	.....	.....

THIRD SERIES—17.2 GRAMS IN OPEN, WIDE-MOUTHED 2-OUNCE BOTTLE.

10 minutes	−0.0025	−0.014	22	61
1½ hours	− .0115	− .067	.....	.....
3½ hours	− .0260	− .15	.....	.....
21 hours	− .0800	− .47	24	36
Stirred and reweighed	− .0020	− .01	.....	.....
24 hours	− .0855	− .50	28	36
Stirred with spoon	− .0020	− .01	.....	.....
26 hours	− .0885	− .51	25	63
Stirred with spoon	− .0015	− .01	.....	.....
42 hours	− .0625	− .36	18	64
Stirred with spoon	− .0010	− .005	.....	.....
4 days	− .1190	− .70	27	35
Stirred with spoon	− .0005	− .003	.....	.....
15 days	− .3625	−2.11	32	41
Stirred with spoon	− .0000	− .000	.....	.....
48 days	− .0200	− .116	32	55
Total loss in 72 days	.....	5.035	.....	.....

A second sample (No. 1638 E) of undried Illinois coal contained 11.89 per cent moisture, and being a duplicate of No. 1638 C, except that it was perhaps more finely pulverized, was also tested in a similar way, by spreading 1 gram on a 3-inch watch glass and 10 grams on a 3-inch watch glass, and by placing 14.5 grams in an open, wide-mouthed 2-ounce bottle. The changes occurring in these three samples are given in the following table:

Changes in moisture content of sample (No. 1638 E) of undried Illinois coal.

FIRST SERIES—1 GRAM ON 3-INCH WATCH GLASS.

Time interval between weighings.	Loss or gain in weight.		Air of laboratory.	
			Temperature.	Humidity.
	Grams.	*Per cent.*	° *C.*	*Per cent.*
5 minutes	−0.0215	−2.15	25	50
5 minutes	− .0160	−1.60	.....	.....
20 minutes	− .0110	−1.10	.....	.....
1½ hours	− .0290	−2.90	25	43
20¾ hours	− .0055	−0.55	24	36
24½ hours	− .0063	−0.63	28	36
25 hours	+ .0143	+1.43	25	63
42 hours	+ .0060	+ .60	18	64
104 hours	− .0142	−1.42	27	35
15 days	+ .0025	+ .25	32	41
48 days	− .0173	−1.73	32	55
Total loss in 72 days	.....	9.80	.....	.....

Changes in moisture content of sample (No. 1638 E) of undried Illinois coal—Continued.

SECOND SERIES—10 GRAMS ON 3-INCH WATCH GLASS.

Time interval between weighings.	Loss or gain in weight.		Air of laboratory.	
			Temperature.	Humidity.
	Grams.	*Per cent.*	° *C.*	*Per cent.*
5 minutes	−0.0518	−0.52	25	50
5 minutes	− .0270	− .27	.....	.....
15 minutes	− .0530	− .53	.....	.....
1½ hours	− .2180	−2.18	25	43
21½ hours	− .2000	−2.00	24	36
24½ hours	− .1937	−1.94	28	36
25 hours	+ .0692	+ .69	25	63
42 hours	+ .0095	+ .095	18	64
104 hours	− .0550	− .55	27	35
15 days	− .0590	− .59	32	41
48 days	− .0870	− .87	32	55
Total loss in 72 days	.....	8.67	.....	.....

THIRD SERIES—14.5 GRAMS IN OPEN, WIDE-MOUTHED 2-OUNCE BOTTLE.

10 minutes	−0.003	−0.02	22	61
1½ hours	− .0135	− .09	.....	.....
3½ hours	− .0310	− .23	.....	.....
21 hours	− .0890	− .60	24	36
Stirred with spoon	− .0020	− .01	.....	.....
24 hours	− .0995	− .68	28	36
Stirred with spoon	− .0025	− .02	.....	.....
26 hours	− .0850	− .56	25	63
Stirred with spoon	− .0015	− .01	.....	.....
42 hours	− .0625	− .42	18	64
Stirred with spoon	− .0010	− .01	.....	.....
104 hours	− .0875	− .60	27	35
Stirred with spoon	− .0015	− .01	.....	.....
15 days	− .2538	−1.71	32	41
Stirred with spoon	− .0010	− .01	.....	.....
48 days	− .0500	− .35	32	55
Total loss in 72 days	.....	5.33	.....	.....

Other experiments were likewise performed on a similar sample (No. 1639 C) of Illinois coal, which contained 4.12 per cent moisture, although the coarse sample had been well air-dried before the preparation of the fine sample. The changes in weight in the 1-gram sample spread on a watch glass, in the 10-gram sample spread on a watch glass, and in a portion (8.3 grams) allowed to stand exposed in an open, wide-mouthed 2-ounce bottle were as follows:

Changes in moisture content of sample (No. 1639 C) of well-dried Illinois coal.

FIRST SERIES—1 GRAM ON 4-INCH WATCH GLASS.

Time interval between weighings.	Loss or gain in weight.		Air of laboratory.	
			Temperature.	Humidity.
	Grams.	*Per cent.*	° *C.*	*Per cent.*
5 minutes	−0.0093	−0.93	28	36
5 minutes	− .0025	− .25	.....	.....
15 minutes	− .0015	− .15	.....	.....
2½ hours	+ .0045	+ .45	.....	.....
23 hours	+ .0135	+1.35	25	63
2 days	+ .0070	+ .70	18	64
4 days	− .0170	−1.70	27	35
14 days	+ .0050	+ .40	32	41
Total loss in 21 days	.....	0.13	.....	.....

Changes in moisture content of sample (No. 1639 C) of well-dried Illinois coal—Continued.

SECOND SERIES—10 GRAMS ON 4-INCH WATCH GLASS.

Time interval between weighings.	Loss or gain in weight.		Air of laboratory.	
			Temperature.	Humidity.
	Grams.	*Per cent.*	° *C.*	*Per cent.*
5 minutes	−0.0190	−0.19	28	36
5 minutes	− .0120	− .12	.....	.....
15 minutes	− .0175	− .175	.....	.....
1 hour	− .0280	− .28	.....	.....
23 hours	+ .1235	+1.24	25	63
2 days	+ .0195	+ .20	18	64
4 days	− .0580	− .58	27	35
14 days	− .0280	− .28	32	41
Total loss in 21 days	.....	0.18	.....	.....

THIRD SERIES—8.3 GRAMS IN OPEN, WIDE-MOUTHED 2-OUNCE BOTTLE.

10 minutes	+0.0015	+0.02	23	69
20 minutes	+ .0010	+ .01	.....	.....
20 minutes	− .0000	.....	.....	.....
5½ hours	+ .0080	+ .08	25	63
2 days	+ .0230	+ .29	18	64
Stirred	− .0000	.....	.....	.....
4 days	+ .0240	+ .29	27	35
14 days	− .0175	− .21	32	41
Stirred	− .0000	− .00	.....	.....
Total gain in 20 days	.....	0.48	.....	.....

An inspection of these results shows that in samples of fine coal prepared from coal not previously air dried the loss may be rapid, being in a 1-gram portion of undried sample over 2 per cent in five minutes and over 8 per cent in twenty-four hours. That samples kept in bottles may lose a considerable amount of moisture unless tightly stoppered is also shown by the results obtained from weighing the samples in an open bottle, the loss in twenty-four hours being nearly 0.7 per cent and in seventy-two hours almost 2 per cent. This loss continued until the total loss in twenty-four days was about 5 per cent. That the danger from losses in handling a fine sample which has been well air dried is not nearly so great is shown by the tests upon No. 1639 C. Upon the 1-gram portion of this sample the loss in five minutes was 0.93 per cent, but the additional loss afterwards was small, showing that the sample was not far from air dry under the existing conditions. In fact, under the conditions existing on the next afternoon the sample as ground was drier than air dry, as is shown by an increase of over 1 per cent in weight. That this sample was about air dry, under the average conditions existing, is furthermore shown by the results obtained on the sample exposed in an open bottle, where the sample at different times shows small losses and small gains in weight. The rapidity with which the 1-gram portion of this dried sample gave up the little moisture it possessed over and above the existing air-dry conditions shows the extreme sensitiveness of finely ground coal samples to changes in the moisture content of the air.

As might be expected, the rapidity of gain or loss is greatest in the 1-gram sample and least in the sample kept in an open bottle. A comparison of these losses after seventy-two days on the undried samples shows, however, that even in that time the loss on the 1-gram sample is decidedly in excess of that on the 10-gram sample, and about twice that on the sample in the open bottle. This result would lead to the inference that the change in weight is not due entirely to moisture losses, but is influenced more or less by oxidation changes. That such is the case is shown by the results of tests of the gain or loss in weight, from time to time, of fine samples kept in tightly stoppered bottles, moisture determinations being made at the same time to find out whether the amount of moisture present in the sample varies with the change in weight. These tests are described under "Alteration of weight of samples of coal when kept in a finely powdered state," pages 19–22.

COMPARISON OF EFFECTS OF DIFFERENT DRYING REAGENTS USED IN THE DESICCATORS EMPLOYED IN MOISTURE DETERMINATIONS.

In the determinations of moisture made during the Louisiana Purchase Exposition and during the earlier part of 1905 duplicate results often were not as close as was desirable. This lack of agreement was found to be due, in part at least, to the use of calcium chloride as a drying reagent in the desiccators in which the fine samples of coal were allowed to cool after drying at 105° C., as may be seen from inspection of the following table giving the values obtained over concentrated sulphuric acid, fused calcium chloride, and granular calcium chloride.

Certain values from samples allowed to stand overnight, which are marked with a star (*), were on different gram portions of the sample. The values given for the other determinations, weighed as soon as cooled and weighed after standing in the desiccator overnight, are on the same weighed-out portions of the sample, which, as soon as weighed the first time, were put back in the desiccator and allowed to stand until the next day and then again weighed. The values over sulphuric acid are, as a rule, about one-tenth of 1 per cent lower on the sample after standing overnight, but this result can probably be accounted for by the small amount of moisture which might be taken up by the sample during the time required for making the first weighing.

Moisture determinations obtained by the use of different drying reagents.

Sample of coal.		Concentrated H_2SO_4.		$CaCl_2$, fused.		$CaCl_2$, granular.	
Laboratory number.	Field number.	1.[a]	2.[b]	1.[a]	2.[b]	1.[a]	2.[b]
1660	Illinois No. 11 B	3.46		3.42 3.38		3.38 3.40	
1786	Illinois No. 13	3.92				3.86	
1802	Illinois No. 11 D	6.34		6.26			
1801	Illinois No. 7 D	2.74				2.74	
1803	Illinois No. 13	7.62		7.46			
1804	do	4.74		4.80			
1794	Alabama	1.38		1.18			
1798	Illinois No. 13	4.96				4.80	
1812	do	3.56		3.46			
1817	Indian Territory	1.42				1.30	
1828	Indiana No. 8	3.62		3.46			
1835	Brazil	4.99	4.92			4.91	4.58
1837	Illinois No. 7 D	3.60	3.60	3.55	3.23		
1807	Indiana No. 4	4.94				4.88	
1808	Illinois No. 12	5.90				5.82	
1836	Illinois No. 13	2.76				2.70	
1838	Illinois No. 18					5.08	
1842	Illinois No. 7 D	1.06		1.02			
1843	Colorado					7.98	7.40
1845	Illinois No. 11 D			4.12	3.46		
1846	Illinois No. 7 D	6.98	6.88	6.90	6.36		
1855	Illinois No. 11 D	1.24	1.14			1.14	.94
1844	Indiana No. 4	3.60				3.56	
1741	Illinois No. 18			3.32	2.58*		
1743	Indian Territory			2.36	1.38*		
1745	do			3.38	2.76*		
1753	Illinois No. 14			12.09	11.56*		

[a] Weighed as soon as cooled.
[b] Weighed after standing in desiccator overnight.

The values obtained over both granular and fused calcium chloride, where the sample was weighed as soon as cooled, are but little lower than the values obtained over sulphuric acid; but the values from the samples over calcium chloride when allowed to stand overnight are so decidedly lower as to show beyond a doubt the superiority of concentrated sulphuric acid over calcium chloride as a desiccating reagent for coal.

EFFECTS OF VARYING AMOUNTS OF SAMPLE AND OF DIFFERENCES IN DURATION OF HEATING ON RESULTS OBTAINED FOR MOISTURE.[a]

The following results were obtained on (1) a very finely ground sample of Illinois coal, and (2) a fine sample of Indiana coal. They show the loss in weight which occurred when the samples were dried for different times, in different amounts, and under different conditions. This change in weight represents not merely the loss of moisture, but includes any changes due to oxidation and other causes. These changes undoubtedly vary with the kind of coal and the condition of the sample.

[a] The official method for the determination of moisture is to heat 1 gram of the fine sample for one hour at 105° C. in a drying oven.

Moisture determinations on Illinois coal (percentages).

Details of treatment.	½-gram sample.	1-gram sample.	2-gram sample.
Loss after 15 minutes' heating at 100° to 107°	8.42	6.65	5.24
Additional loss after another 15 minutes' heating at 100° to 107°	.84	2.62	3.70
Total loss after 30 minutes' heating	9.26	9.27	8.94
Additional loss after heating another 30 minutes at 100° to 107°	.06	.16	.43
Total loss after 1 hour's heating	9.32	9.43	9.37
Gain in weight by standing uncovered 41 hours	3.68	3.68	3.55
Total loss after heating another 30 minutes	8.86	9.20	9.27
Gain in weight after standing 41 hours and reheating as compared with the value at the end of 1 hour's heating	.46	.23	.10

Moisture determinations on Indiana coal (percentages).

Details of treatment.	½-gram sample.	1-gram sample.	2-gram sample.	4-gram sample.
Loss after 30 minutes' heating at 105°	5.50	5.60 to 5.58	5.62 to 5.61	5.49
Loss after heating another 30 minutes at 105°	.04	.08 to .04	.07 to .02	.15
Total loss after 1 hour's heating	5.54	5.68 to 5.62	5.69 to 5.63	5.64
Gain in weight by standing uncovered 20 hours	3.44	3.43 to 3.35	3.41 to 3.35	3.34
Total loss after heating another hour at 105°	5.20	5.45 to 5.37	5.53 to 5.48	5.55
Gain in weight after 20 hours' standing and 1 hour's reheating compared with weight after first hour's heating	.34	.23 to .25	.16 to .15	.09
Gain in weight by standing uncovered 120 hours	3.06	3.12 to 2.95	3.15 to 3.11	3.12
Total loss after heating another hour at 105°	4.90	5.14 to 5.10	5.19 to 5.17	5.21
Gain in weight compared with weight after the first hour's heating	.64	.54 to .52	.50 to .46	.43
Gain in weight by standing uncovered 24 days	3.70	3.62 to 3.58	3.52 to 3.51	3.45
Total loss after another hour's heating at 105°	4.20	4.60 to 4.62	4.72 to 4.70	4.77
Gain in weight compared with weight after first hour's heating	1.34	1.08 to 1.00	.97 to .93	.87

These results show that practically all of the moisture is expelled from coals of these kinds during the first thirty minutes, and, furthermore, that there was an appreciable amount of oxidation in the sample during standing or from reheating. For short periods this oxidation value in these experiments was apparently a surface reaction, dependent on the surface exposure of the sample and not on the amount. The samples were all weighed out in porcelain crucibles of the same size, and the amount of sample directly exposed was practically the same in all. In this case the percentage effect of equal oxidation on the Illinois samples would be in the ratio of 4, 2, and 1. The gains actually determined at the end of 41 hours were 0.46, 0.23, and 0.10 per cent, respectively, which are very close to this ratio.

On the Indiana sample the gains for oxidation at the end of twenty hours were 0.34, 0.24, 0.15, and 0.09 per cent, respectively. At the end of twenty-four days the percentages of gain on the different amounts are more nearly the same, but the gain is still greatest on the ½-gram sample and least on the 4-gram sample, the gains on the four amounts taken being 1.34, 1.04, 0.95, and 0.87 per cent, respectively.

ALTERATION OF WEIGHT OF SAMPLES OF COAL WHEN KEPT IN A FINELY POWDERED STATE.

In order to investigate the question of the extent of alteration of the samples when kept in a finely powdered condition as prepared for analysis, portions of a number of such samples were put in weighed

bottles, which were securely closed with rubber stoppers. These bottles were kept in the laboratory and weighed from time to time. Moisture determinations were made on portions of the sample at the times of the weighings, allowance being made for the portions removed for this purpose. The following table gives the percentage of moisture originally present in the sample, the percentage of gain or loss in weight at the several weighings, and the time interval between the weighings; also the total time covered by the experiment:

Alteration of weight of finely powdered coal.

[Minus sign denotes loss.]

Sample of coal.		Days between weighings.	Change in weight.	Moisture determination.
Laboratory number.	Field number.			
			Per cent.	*Per cent.*
1635	Illinois No. 9 A	.....	.....	5.10
		4	0.17	5.13
		20	.47	5.31
		42	.46	5.36
		25	.19	5.29
		172	.00	4.99
		124	−.33	4.38
		387	.96	−.72
1638 C	Illinois No. 9 B	.....	.....	12.34
		4	.16	12.58
		19	.45	12.12
		27	.22	12.03
		41	.23	11.79
		172	.00	11.62
		263	1.06	−.72
1638 E	.....do	.....	.....	11.89
		4	.17	11.97
		46	1.07	11.80
		41	.40	11.64
		191	.00	11.06
		282	1.64	−.83
1639	.....do	.....	.....	4.03
		23	.61	4.03
		42	.47	4.38
		34	.31	4.53
		163	.27	4.37
		127	−.12	4.23
		389	1.54	.20
1660	Illinois No. 11 B	.....	.....	3.25
		15	.40	3.26
		27	.42	3.47
		50	.43	3.89
		183	.10	3.60
		107	.00	3.57
		382	1.35	.32
1844	Indiana No. 4	.....	.....	3.58
		7	.22	3.79
		34	.48	3.90
		183	.58	3.87
		107	.14	3.63
		331	1.37	.05
1867	West Virginia No. 13	.....	.....	1.03
		24	.24	1.16
		191	.15	1.21
		108	.07	1.09
		323	.46	.06

Alteration of weight of finely powdered coal—Continued.

[Minus sign denotes loss.]

Sample of coal.		Days between weighings.	Change in weight.	Moisture determination.
Laboratory number.	Field number.			
			Per cent.	*Per cent.*
2062	Ohio No. 5	.....	.....	1.99
		9	.22	.....
		18	.22	.....
		149	.40	2.49
		108	.13	2.43
		284	.97	.44
2131	Wyoming No. 2	.....	.....	4.65
		2	.04	.....
		3	.06	.....
		24	.18	.....
		7	.10	.....
		43	.09	.....
		28	.00	.....
		55	.06	4.55
		107	.02	4.46
		269	.55	−.19
2243	North Dakota No. 3	.....	.....	26.64
		4	.05	.....
		3	.03	.....
		7	.08	.....
		43	.23	.....
		28	.07	.....
		55	.16	25.91
		107	−.05	25.64
		247	.57	−1.00
2275	Wyoming No. 2 B	.....	.....	6.37
		2	.05	.....
		7	.05	.....
		43	.13	.....
		28	.02	.....
		55	.06	6.15
		135	.31	−.22
2278	Wyoming No. 3	.....	.....	12.59
		2	.09	.....
		7	.22	.....
		43	.68	.....
		28	.15	.....
		55	.38	11.97
		107	.26	11.81
		242	1.78	−.78
2255	North Dakota No. 3	.....	.....	12.62
		2	.02	.....
		5	.17	.....
		43	.34	.....
		28	.15	.....
		56	.16	12.86
		134	.84	.24
2718	Texas No. 4	.....	.....	33.00
		6	.29	.....
		42	.24	.....
		3	.03	32.87
		51	.56	−.13
2828	Massachusetts peat	.....	.....	13.60
		8	.07	.....
		13	.09	.....
		3	.00	13.72
		103	−.72	13.16
		127	−.56	−.44

Without exception these samples all increased in weight upon standing. At the same time the moisture values usually decreased. The gain in weight is to be ascribed to oxidation, and the decrease in moisture either to actual loss or to fixation of a portion of the moisture present by the oxidation changes. If the moisture loss be considered as an actual escape of moisture from the sample, the total gain due to oxidation is equal to the observed gain plus an amount equal to this moisture loss. The table below gives the total oxidation changes considered on this basis, together with the original and final calorimeter determinations on some of the samples, also the loss in calorific value in excess of that due merely to changes in weight of the sample. For purposes of comparison the amounts of moisture, ash, and sulphur present in the sample are also given.

Determinations of oxidation, calorific value, moisture, ash, and sulphur.

[Minus sign denotes loss.]

Sample of coal.		Increase in weight due to oxidation.	Calorific value.			Moisture.	Ash.	Sulphur.
Laboratory number.	Field number.		Original.	Final.	Gain or loss above that accounted for by oxidation.			
		Per cent.	*Calories.*	*Calories.*	*Calories.*	*Per cent.*	*Per cent.*	*Per cent.*
1635	Illinois No. 9 A	1.68	.....	.....	.....	4.99	11.80	4.43
1638C	Illinois No. 9 B	1.78	.....	.....	.....	12.34	.....	.....
1638E	do	2.47	.....	.....	.....	11.89	.....	.....
1639	do	1.34	.....	.....	.....	4.03	11.48	4.40
1660	Illinois No. 11 B	1.03	.....	.....	.....	3.25	12.38	2.62
1844	Indiana No. 4	1.32	6,426	6,265	−77	3.58	16.05	2.59
2828	Massachusetts peat	1.00	4,055	4,049	35	13.60	20.74	.58
2243	North Dakota No. 3	1.57	4,498	4,431	3	26.64	8.88	1.32
2255	do	.60	.....	.....	.....	12.62	8.77	1.22
2062	Ohio No. 5	.53	7,501	7,375	−86	1.99	7.48	1.76
2718	Texas No. 4	.69	.....	.....	.....	33.00	7.66	.....
1867	West Virginia No. 13	.40	8,408	8,359	−17	1.03	2.40	.83
2131	Wyoming No. 2	.74	5,815	5,747	−26	4.64	21.77	4.22
2275	Wyoming No. 2 B	.53	.....	.....	.....	6.37	19.69	4.09
2278	Wyoming No. 3	2.56	5,108	4,903	−75	12.59	17.20	6.86

The oxidation changes in every case are sufficiently large to be of practical importance, the smallest change—that in the Ohio No. 5 sample—being 0.53 per cent, while the Illinois No. 9 B sample showed a change of 2.47 per cent. The Wyoming No. 3 sample showed an increase of 2.56 per cent in weight and a decrease of 205 calories in heating value. The changes in weight correspond to a decrease in heating value of 144 calories, the final calorific value obtained being 75 calories lower than is accounted for by the changes in weight. Further results along these lines are desirable, but the values already obtained show very clearly that old samples of coal can not be regarded as representative of the original coal in composition or in calorific value.

DETERMINATIONS OF SPECIFIC GRAVITIES OF THE COALS.

Two determinations of specific gravity were made on a number of lumps about 1 inch in diameter. The first determination was made upon a number of specially selected lumps representing as clean coal as could be picked out, carefully avoiding portions contaminated with slate or pyrites; the second was made upon a number of lumps selected to represent the average quality of the coal as nearly as could be expected in pieces of this size. The determinations of each kind were made (in duplicate and sometimes in triplicate) with a large Nicholson's hydrometer designed for use with the coke samples and capable of handling 1,000 grams of coal. The following table gives the results on the two kinds of lumps. For ease of reference and for comparison the determinations of ash and sulphur on the car samples of each coal are also tabulated.

Determinations of ash, sulphur, and specific gravity.

Designation of coal sampled.	Car sample.		Specific gravity.	
	Ash.	Sulphur.	Selected lumps.	Average lumps.
Alabama No. 2 B	14.59	1.12	1.32	1.37
Alabama No. 3	14.36	.55	1.30	1.38
Alabama No. 4	12.92	1.08	1.28	1.32
Arkansas No. 7 A	11.69	2.02	1.32	1.44
Brazil	21.93	2.72	1.37	1.40
Illinois No. 19 B	9.36	.91	1.31	1.33
Illinois No. 23 A	11.53	4.41	1.22	1.26
Illinois No. 25	13.40	4.76	1.26	1.30
Illinois No. 26	12.09	3.51	1.22	1.31
Illinois No. 27	13.77	4.05	1.24	1.28
Indiana No. 5	10.88	4.27	1.28	1.42
Indiana No. 6	12.62	4.39	1.25	1.39
Indiana No. 7 A	9.21	3.74	1.27	1.40
Indiana No. 8	10.61	3.72	1.29	1.30
Indiana No. 9 A	10.30	3.27	1.25	1.36
Indiana No. 9 B	10.76	3.15	1.25	1.33
Indiana No. 10	8.57	3.83	1.24	1.29
Indiana No. 11	8.14	1.41	1.26	1.30
Indiana No. 12	11.65	3.87	1.26	1.32
Kansas No. 6	15.72	3.72	1.23	1.34
Kentucky No. 1 B	3.37	.88	1.27	1.40
Kentucky No. 5	3.70	.67	1.29	1.30
Kentucky No. 6	2.76	.57	1.27	1.28
Kentucky No. 7	9.48	3.60	1.31	1.44
Maryland No. 1	13.13	1.49	1.36	1.41
Missouri No. 6	11.74	5.60	1.21	1.36
New Mexico No. 3	16.67	.73	1.29	1.37
New Mexico No. 4 A	14.57	.61	1.30	1.39
New Mexico No. 5	14.57	.69	1.31	1.35
North Dakota No. 1 B	11.42	3.54	1.25	1.44
North Dakota No. 3	7.75	1.15	[a] 1.22	
Ohio No. 1	11.95	4.61	1.29	1.35
Ohio No. 2	11.33	4.02	1.31	1.36
Ohio No. 3	11.58	1.81	1.30	1.33
Ohio No. 4	9.12	3.47	1.30	1.39
Ohio No. 5	7.30	1.72	1.29	1.33
Ohio Nos. 6 A, 6 B	8.52	3.33	1.29	1.35
Ohio No. 7	6.37	2.16	1.30	1.34
Ohio No. 8 A	8.37	2.84	1.30	1.42
Ohio No. 9 A	8.29	3.15	1.29	1.31
Ohio No. 9 B	11.93	3.35	1.30	1.36
Pennsylvania No. 4	10.41	1.26	1.30	1.35
Pennsylvania No. 5 A	6.02	1.20	1.30	1.31
Pennsylvania No. 5 B	6.05	.88	1.28	1.33
Pennsylvania No. 6	13.00	1.95	1.30	1.33
Do	12.52	1.94	1.30	1.38
Pennsylvania No. 7 A, 7 B	12.47	2.08	1.33	1.41
Pennsylvania No. 8	6.63	.94	1.31	1.36
Pennsylvania No. 9	11.33	2.04	1.35	1.39

[a] No distinction made between clean or selected lumps and average lumps.

Determinations of ash, sulphur, and specific gravity—Continued.

Designation of coal sampled.	Car sample.		Specific gravity.	
	Ash.	Sulphur	Selected lumps.	Average lumps.
Pennsylvania No. 10	6.17	1.26	1.30	1.36
Tennessee No. 2	6.81	.98	1.28	1.33
Tennessee No. 3	7.05	.99	1.29	1.32
Tennessee No. 4	9.53	.98	1.29	1.37
Tennessee No. 6	14.43	.78	1.29	1.31
Tennessee No. 7 A	12.85	3.26	1.34	1.39
Tennessee No. 8 A	13.42	4.38	1.34	1.37
Tennessee No. 10	59.14	.21	1.35	.....
Texas No. 3	7.88	.99	.....	1.25
Texas No. 4	7.30	.51	.....	1.26
Virginia No. 1 A	4.73	1.20	1.27	1.30
Virginia No. 1 B	5.01	1.11	1.27	1.34
Virginia No. 2 B	5.58	.92	1.28	1.37
Virginia No. 3	4.48	.67	1.27	1.28
Virginia No. 4	4.33	.79	1.28	1.28
Washington No. 1 B	11.37	.72	1.28	1.33
Washington No. 2	12.26	.38	1.32	1.39
West Virginia No. 4 B	7.76	.81	1.31	1.35
West Virginia No. 13	3.91	.89	1.27	1.30
West Virginia No. 14	3.27	1.03	1.27	1.28
West Virginia No. 15	8.55	2.54	1.28	1.31
West Virginia No. 16 A	5.57	1.06	1.30	1.37
West Virginia No. 16 B	8.37	1.20	1.28	1.34
West Virginia No. 17	8.12	1.45	1.28	1.41
West Virginia No. 18	5.83	.67	1.30	1.34
West Virginia No. 19	5.01	.89	1.26	1.38
West Virginia No. 20	8.03	1.38	1.27	1.34
West Virginia No. 21	4.85	1.32	1.28	1.34
Wyoming No. 2 B	20.79	4.03	1.31	1.37
Wyoming No. 3	16.70	6.66	1.28	1.40
Wyoming No. 4	6.77	.26	1.33	1.35
Wyoming No. 5	3.41	.81	1.26	1.30
Wyoming No. 6	3.12	.49	1.28	.....

It is obvious from the foregoing table that the specific gravity of the lumps of coal is considerably affected by the amount of impurities contained. Even the selected lumps were not free from ash and sulphur, so that it is not possible to obtain the true specific gravity of the pure coal itself.

In order to further investigate the relation of impurities to specific gravity, five of the coals in the foregoing table were selected as representing the great diversity of character. These coals were separated first into sizes and then each size, except the dust, was further separated by "float-and-sink" tests upon heavy solutions, of 1.35 specific gravity calcium chloride and 1.45 and 1.65 specific gravity zinc chloride. The procedure in detail was as follows:

The coal, after crushing till it all passed a ½-inch screen, was sifted over a series of sieves—80 mesh, 40 mesh, 10 mesh, and 4 mesh. That passing the first two screens was designated "dust;" that passing the 10 mesh and retained on the 40 mesh was designated "fine;" that passing the 4 mesh and retained on the 10 mesh "medium," and that retained on the 4 mesh "coarse." The dust was not separated on the solution, but each of the remaining classes was then stirred in a solution of 1.35 specific gravity, and the floating coal was removed, washed, and air dried. That sinking in this solution was then washed, dried, weighed, and stirred in a solution of 1.45 specific gravity, and the floating coal treated as before; and the process was again repeated in a solution of

1.65 specific gravity with the coal that sank. Each product was washed, air dried, and analyzed.

The results are given in the following table. Column 1 gives the percentage that the amount of coal in each grade of fineness forms of the entire sample treated; column 2, the percentage that the amount of coal in each class separated by gravity forms of the amount in its grade of fineness, and column 3, the percentage that the amount of coal in each class forms of the entire sample. Column 4 gives the determination of the ash in each class, expressed as a percentage of the amount of coal in the class; column 5, this determination of the ash expressed as a percentage of the entire sample of coal, and columns 6 and 7 give the same percentages for the sulphur. The totals of the results for ash and sulphur, in columns 5 and 7, should obviously equal the ash and sulphur determinations, respectively, in the original coal, which are printed below them for purposes of comparison. The differences are due to unavoidable errors in the work and, in some cases, probably in part to the presence of sulphates extracted in washing.

Impurities in coal as related to different grades of fineness and classes of specific gravity.

NO. 2023, BRAZIL NO. 1.[a]

Grade and class of coal.	Mechanical distribution of coal.			Amount of ash in each class.		Amount of sulphur in each class.	
	Per cent of entire sample in each grade.	Amount in each class.		As per cent of coal in the class.	As per cent of entire sample of coal.	As per cent of coal in the class.	As per cent of entire sample of coal.
		Per cent of its own grade.	Per cent of entire sample.				
	1.	2.	3.	4.	5.	6.	7.
Dust {80	3.95	56.43	.....	28.64	1.131	1.90	0.075
Dust {80 to 40	3.05	43.57	.....	26.35	.804	1.60	.049
Sum	7.00	100.00	7.00				
Fine, 40 to 10	18.10	.....	.....	.....	.....	.....	.....
Specific gravity—							
Under 1.35	.....	62.11	11.15	11.64	1.298	.61	.068
1.35 to 1.45	.....	2.23	.40	15.33	.061	.84	.003
1.45 to 1.65	.....	17.83	3.20	30.22	.967	.615	.020
Above 1.65	.....	17.83	3.20	54.49	1.744	5.41	.173
Sum	.....	100.00	17.95				
Medium, 10 to 4	30.45	.....	.....	.....	.....	.....	.....
Specific gravity—							
Under 1.35	.....	55.53	17.55	13.90	2.439	.60	.105
1.35 to 1.45	.....	3.64	1.15	23.38	.269	.59	.007
1.45 to 1.65	.....	28.01	8.85	33.38	2.954	.55	.049
Above 1.65	.....	12.82	4.05	55.08	2.231	8.92	.361
Sum	.....	100.00	31.60				
Coarse, 4 to 2	44.60	.....	.....	.....	.....	.....	.....
Specific gravity—							
Under 1.35	.....	45.10	21.20	17.33	3.674	.64	.136
1.35 to 1.45	.....	3.19	1.50	26.52	.398	.50	.007
1.45 to 1.65	.....	31.92	15.00	32.74	4.911	.66	.099
Above 1.65	.....	19.79	9.30	59.08	5.494	21.24	1.975
Sum	.....	100.00	47.00				
Total	100.15	.....	103.55	.....	28.375	.....	3.127
Original sample	.....	.....	.....	.....	28.18	.....	4.28

[a] Sp. gr. of average lumps, 1.40; of selected lumps, 1.37.

Impurities in coal as related to different grades of fineness, etc.—Continued.

NO. 2346, MARYLAND NO. 1.[a]

Grade and class of coal.	Mechanical distribution of coal.			Amount of ash in each class.		Amount of sulphur in each class.	
	Per cent of entire sample in each grade.	Amount in each class.		As per cent of coal in the class.	As per cent of entire sample of coal.	As per cent of coal in the class.	As per cent of entire sample of coal.
		Per cent of its own grade.	Per cent of entire sample.				
	1.	2.	3.	4.	5.	6.	7.
Dust {80	5.05	52.06	.....	15.47	0.781	2.00	0.101
Dust {80 to 40	4.65	47.94	.....	12.99	.604	1.55	.072
Sum	9.70	100.00	9.70				
Fine, 40 to 10	33.45	.....	.....	.....	.....	.....	.....
Specific gravity—							
Under 1.35	.....	81.40	27.10	6.25	1.694	.92	.249
1.35 to 1.45	.....	10.07	3.35	13.62	.456	1.25	.042
1.45 to 1.65	.....	3.75	1.25	25.02	.313	2.21	.028
Above 1.65	.....	4.78	1.60	61.48	.984	9.04	.145
Sum	.....	100.00	33.30				
Medium, 10 to 4	41.95	.....	.....	.....	.....	.....	.....
Specific gravity—							
Under 1.35	.....	63.60	26.65	5.57	1.484	.84	.224
1.35 to 1.45	.....	25.54	10.70	13.77	1.473	1.21	.129
1.45 to 1.65	.....	5.85	2.45	25.63	.628	2.36	.058
Above 1.65	.....	5.01	2.10	57.63	1.210	8.14	.171
Sum	.....	100.00	41.90				
Coarse, 4 to 2	14.70	.....	.....	.....	.....	.....	.....
Specific gravity—							
Under 1,35	.....	39.15	5.75	6.45	.371	.84	.048
1.35 to 1.45	.....	38.10	5.60	14.16	.793	1.07	.060
1.45 to 1.65	.....	10.84	1.60	25.68	.411	2.48	.040
Above 1.65	.....	11.91	1.75	55.90	978	7.28	.127
Sum	.....	100.00	14.70				
Total	99.80	.....	99.60	.....	12.180	.....	1.49
Original sample	.....	.....	.....	.....	12.53	.....	1.51

NO. 2308, PENNSYLVANIA NO. 6.[b]

Dust {80	5.50	55.85	.....	14.74	0.811	2.36	0.130
Dust {80 to 40	4.35	44.15	.....	12.35	.537	2.19	.095
Sum	9.85	100.00	9.85				
Fine, 40 to 10	20.40	.....	.....	.....	.....	.....	.....
Specific gravity—							
Under 1.35	.....	88.36	17.85	6.44	1.149	1.10	.196
1.35 to 1.45	.....	2.97	.60	17.55	.105	2.75	.016
1.45 to 1.65	.....	1.98	.40	28.26	.113	4.04	.016
Above 1.65	.....	6.69	1.35	67.45	.911	10.20	.138
Sum	.....	100.00	20.20				
Medium, 10 to 4	29.75	.....	.....	.....	.....	.....	.....
Specific gravity—							
Under 1.35	.....	81.38	24.25	6.15	1.491	1.10	.267
1.35 to 1.45	.....	9.06	2.70	16.97	.458	2.39	.065
1.45 to 1.65	.....	2.68	.80	29.70	.238	3.42	.027
Above 1.65	.....	6.88	2.05	63.95	1.311	11.39	.233
Sum	.....	100.00	29.80				
Coarse, 4 to 2	39.70	.....	.....	.....	.....	.....	.....
Specific gravity—							
Under 1.35	.....	70.42	27.95	6.21	1.736	1.07	.299
1.35 to 1.45	.....	13.86	5.50	16.37	.900	2.33	.128
1.45 to 1.65	.....	4.78	1.90	29.57	.562	2.47	.047
Above 1.65	.....	10.94	4.35	66.20	2.880	7.06	.307
Sum	.....	100.00	39.70				
Total	99.70	.....	99.55	.....	13.202	.....	1.964
Original sample	.....	.....	.....	.....	12.61	.....	1.76

[a] Sp. gr. of average lumps, 1.41; of selected lumps, 1.36.
[b] Sp. gr. of average lumps, 1.33; of selected lumps, 1.30.

Impurities in coal as related to different grades of fineness, etc.—Continued.

NO. 2298, WEST VIRGINIA NO. 15.[a]

Grade and class of coal.	Mechanical distribution of coal.			Amount of ash in each class.		Amount of sulphur in each class.	
	Per cent of entire sample in each grade.	Amount in each class.		As per cent of coal in the class.	As per cent of entire sample of coal.	As per cent of coal in the class.	As per cent of entire sample of coal.
		Per cent of its own grade.	Per cent of entire sample.				
	1.	2.	3.	4.	5.	6.	7.
Dust {80	5.35	55.15	5.35	10.35	0.554	3.42	0.183
Dust {80 to 40	4.35	44.85	4.35	8.27	.360	3.10	.115
Sum	9.70	100.00	9.70				
Fine, 40 to 10	22.65						
Specific gravity—							
Under 1.35	.....	92.68	20.90	4.39	.917	1.62	.338
1.35 to 1.45	.....	1.33	.30	13.63	.041	6.37	.019
1.45 to 1.65	.....	.89	.20	22.75	.046	10.10	.020
Above 1.65	.....	5.10	1.15	57.78	.671	26.95	.310
Sum	.....	100.00	22.55				
Medium, 10 to 4	33.20						
Specific gravity—							
Under 1.35	.....	90.65	30.05	4.56	1.370	1.59	.478
1.35 to 1.45	.....	3.77	1.25	13.40	.167	6.48	.081
1.45 to 1.65	.....	1.81	.60	22.89	.137	10.25	.061
Above 1.65	.....	3.77	1.25	53.03	.663	26.26	.328
Sum	.....	100.00	33.15				
Coarse, 4 to 2	34.30						
Specific gravity—							
Under 1.35	.....	86.30	29.60	5.40	1.597	1.73	.512
1.35 to 1.45	.....	6.42	2.20	13.10	.288	6.40	.141
1.45 to 1.65	.....	3.49	1.20	24.88	.298	7.40	.089
Above 1.65	.....	3.79	1.30	66.15	.860	13.05	.171
Sum	.....	100.00	34.30				
Total	99.85	.....	99.70	.....	7.969	.....	2.846
Original sample	.....	.....	.....	.....	7.34	.....	2.82

NO. 2278, WYOMING NO. 3.[b]

Dust {80	2.05	54.62	.....	23.45	0.481	8.89	0.182
Dust {80 to 40	1.70	45.38	.....	19.43	.330	8.21	.139
Sum	3.75	100.00	3.75				
Fine, 40 to 10	11.50						
Specific gravity—							
Under 1.35	.....	74.12	8.30	5.46	.453	4.91	.407
Above 1.35	.....	25.88	2.90	47.51	1.378	14.43	.418
Sum	.....	100.00	11.20				
Medium, 10 to 4	29.85						
Specific gravity—							
Under 1.35	.....	77.03	22.65	5.54	1.255	4.72	1.069
Above 1.35	.....	22.97	6.75	47.98	3.239	15.54	1.049
Sum	.....	100.00	29.40				
Coarse, 4 to 2	54.85						
Specific gravity—							
Under 1.35	.....	69.65	38.20	6.53	2.494	4.66	1.780
Above 1.35	.....	30.35	16.65	50.03	8.330	18.04	3.004
Sum	.....	100.00	54.85				
Total	99.95	.....	99.20	.....	17.960	.....	8.048
Original sample	.....	.....	.....	.....	17.96	.....	8.36

[a] Sp. gr. of average lumps, 1.31; of selected lumps, 1.28.
[b] Sp. gr. of average lumps, 1.40; of selected lumps, 1.28.

An examination of the figures in the foregoing table shows the very rapid increase in impurity of the coal with increase in specific gravity. The finer the coal is crushed the more complete would be the mechanical separation of the heavy impurities from the coal, but the behavior in this respect evidently varies greatly with different coals. In the Brazil coal the sulphur is nearly the same in all the coal under ½-inch size and below 1.65 specific gravity, while the ash increases both with size and with the specific gravity. In the Maryland coal both sulphur and ash increase with specific gravity, and apparently without very much reference to size of product. Practically the same is true of the Pennsylvania No. 6 coal and of the West Virginia coal. The record of the Wyoming coal is not sufficiently complete for comparison. In all but the Brazil coal there is a marked tendency to increase of ash and sulphur in the fine dust, suggesting that the impurities are liberated in crushing and are more brittle than the mass of the coal. Noticeably different compositions in ash and sulphur of the portions of the various coals below 1.35 specific gravity, may indicate either actual variations in the specific gravity of the coal proper or variations in the nature of the combination of the sulphur and mineral matter.

Further experiments along these lines seem very desirable.

LABORATORY METHODS OF DETERMINING ADAPTABILITY OF COALS TO IMPROVEMENT BY WASHING.

The laboratory method of testing consists in floating the sample upon solutions of different density and thereby separating the coal into portions of different specific gravity, the amounts of these portions being determined and each portion analyzed separately for ash and sulphur, as noted under the last heading. The samples used were crushed to one-half inch and finer before testing, and for convenience in handling were divided by sifting into two portions, one one-half inch to one-fortieth inch, the other one-fortieth inch and finer. On some of the earlier samples the division was made at one-twentieth inch. The solutions used for washing the samples were a calcium-chloride solution of 1.35 specific gravity and a zinc-chloride solution of 1.65 specific gravity. Solutions of 1.45 and 1.90 specific gravity were also used occasionally. The clean coal, low in ash, floats upon a solution of 1.35 specific gravity. Moderately high-ash coal sinks in a solution of this gravity, but floats upon a solution of 1.45 specific gravity. Coal very high in ash is heavier than 1.45, but floats upon a solution of about 1.65 specific gravity, while the slate and pyrites sink in solution of this gravity. The results obtained by washing the samples upon these different solutions and the analysis of the resultant products, together with the analysis of the original sample and the analysis of samples obtained from actual washing tests made at the washery connected with the fuel-testing plant upon 5- to 6-ton lots of

certain of the coals, are given in the tables of results below. As these laboratory samples were all crushed to one-half inch and finer before testing, these results do not necessarily show what might be done with the coal crushed to other sizes. They do, however, give an indication of the possible improvements which may be expected from washing.

The "one-fortieth inch and finer" portion of the sample was tested as follows: The sample was stirred up with water, and after settling for one minute the liquid was decanted off very closely and the remaining portion was dried, weighed, and analyzed. The loss on decantation indicates in a very general way the extent to which the coal breaks down into a fine powder upon handling or crushing, and is an indication of the amount of fine coal lost during washing. The particular crushing machinery used would, however, greatly affect the amount of fines produced in crushing. The analytical results on the portion remaining after decantation are in a general way an index to the way the impurities separate from the coal in crushing.

The interpretation of these results may perhaps be understood best by a consideration of the results derived from some particular sample, as Indiana No. 7 A. In this sample the ash and sulphur contents in the unwashed coal are, respectively, 9.03 and 3.75. The sample crushed to "$\frac{1}{2}$ inch to $\frac{1}{40}$ inch" was separated by sifting into 91.1 per cent coarse and 8.6 per cent fine. Considering the coarse portion: The part lighter than 1.35 specific gravity amounted to 86.7 per cent of the entire sample, and contained 6.69 per cent ash and 3.05 per cent sulphur. It is quite probable that in actual washing practice a large part of the "$\frac{1}{40}$ inch and finer" would be reduced in ash and sulphur contents to about the same percentage, which would indicate the possibility of improving this coal 2 per cent in ash and 0.7 per cent in sulphur, accompanied by a washing loss of about 10 per cent. The distribution of the ash and sulphur on the heavier portion is shown by the percentage results on the "1.35 to 1.65" portion and on the portion "Heavier than 1.65." The washery tests do not show so great an improvement in ash and sulphur as might be expected from the analysis of the portion "Lighter than 1.35," and a portion of the "1.35 to 1.65" specific gravity material evidently remained with the washed coal. However, washery tests upon such small lots of coal can not be expected to give the best results; also the possible improvement at $\frac{1}{2}$-inch size is apt to be greater than can be obtained at $1\frac{1}{4}$-inch size, at which the sample was worked at the washery. The results of the laboratory tests indicate that the high sulphur and the comparatively high ash in the washed coal from the washery is not the fault of the washing, but is due to the combination in which the ash and sulphur occur, showing that a very low ash and sulphur product can not be obtained from this coal by washing. The laboratory tests do, how-

ever, indicate that under the best conditions of washing there would be some improvement, but not much, over the results obtained at the washery of the fuel-testing plant.

Determinations of ash and sulphur in coal samples variously treated.

ILLINOIS NO. 9 A.

[Unwashed coal—ash, 11.21; sulphur, 4.53.]

	Portion.	Ash.	Sulphur.	Compared with original sample.	
				Ash.	Sulphur.
First series:					
¼ inch to 1/16 inch	91.9				
Lighter than 1.35	75.2	6.08	3.16	4.57	2.38
1.35 to 1.65	12.1	21.04	4.80	2.55	.58
Heavier than 1.65	4.2	58.34	16.93	2.45	.71
1/16 inch and finer	9.0				
Very fine, decanted [a]	2.3			.26	.10
Remainder	5.6	13.88	4.20	.78	.24
				10.61	4.01
Second series:					
¼ inch to 1/16 inch	91.9				
Lighter than 1.45	84.9	8.22	3.32	6.98	2.82
Heavier than 1.45	7.7	44.02	14.12	3.39	1.09
1/16 inch and finer	7.7				
Very fine, decanted [a]	2.4			.27	.11
Remainder	5.6	13.88	4.20	.78	.24
				11.42	4.26
Washed at 1½-inch size:					
Sample No. 1		8.14	3.63		
No. 2		8.26	3.71		

ILLINOIS NO. 11 B.

[Unwashed coal—ash, 12.54; sulphur, 2.86.]

¼ inch to 1/16 inch	80.1				
Lighter than 1.35	56.5	5.71	1.72	3.22	0.97
1.35 to 1.65	16.1	17.49	2.48	2.82	.40
Heavier than 1.65	5.7	58.42	11.91	3.33	.68
1/16 inch and finer	19.5				
Very fine, decanted [a]	5.8			.73	.17
Remainder	13.7	17.42	3.15	2.39	.43
				12.49	2.65

ILLINOIS NO. 19 B.

[Unwashed coal (boiler-test sample, No. 2044)—ash, 10.57; sulphur, 0.49.]

¼ inch to 1/16 inch	92.8				
Lighter than 1.35	80.9	4.79	0.63	3.88	0.51
1.35 to 1.65	5.6	27.03	.52	1.51	.03
Heavier than 1.65	6.5	65.75	.29	4.28	.02
1/16 inch and finer	6.9				
Very fine, decanted [a]	3.5			.37	.02
Remainder	3.4	16.05	.60	.55	.02
				10.59	.60

[a] Estimated from results on unwashed coal.

Determinations of ash and sulphur in coal samples variously treated—Continued.

INDIANA NO. 4.

[Unwashed coal (boiler-test sample, NO. 1892)—ash, 15.63; sulphur, 2.74.]

	Portion.	Ash.	Sulphur.	Compared with original sample.	
				Ash.	Sulphur.
¼ inch to 1/16 inch	81.9				
Lighter than 1.35	61.8	5.89	1.82	3.66	1.12
1.35 to 1.65	11.9	17.50	3.54	2.10	.42
Heavier than 1.65	8.9	69.29	7.01	6.17	.62
1/16 inch and finer	17.5				
Very fine, decanted [a]	5.3			.83	.15
Remainder	12.2	23.83	2.84	2.88	.35
				15.64	2.66
Washed at 1¼-inch size:					
Sample No. 1		8.26	2.26		
No. 2		7.69	2.26		

INDIANA NO. 6.

[Unwashed coal (boiler-test sample, No. 1928)—ash, 13.54; sulphur, 4.83.]

¼ inch to 1/16 inch	76.1				
Lighter than 1.35	56.2	6.63	2.92	3.73	1.64
1.35 to 1.65	13.6	19.58	5.54	2.66	.75
Heavier than 1.65	6.7	54.89	13.75	3.68	.91
1/16 inch and finer	23.2				
Very fine, decanted [a]	6.9			.93	.33
Remainder	16.3	17.10	5.19	2.79	.85
				13.79	4.48
Washed at 1¼-inch size:					
Sample No. 1		10.34	3.67		
No. 2		10.98	3.94		
No. 3		10.06	3.73		

INDIANA NO. 7 A.

[Unwashed coal (boiler-test sample, No. 1939)—ash, 9.03; sulphur, 3.75.]

¼ inch to 1/16 inch	91.1				
Lighter than 1.35	86.7	6.69	3.05	5.80	2.64
1.35 to 1.65	3.6	26.23	4.39	.94	.16
Heavier than 1.65	3.4	55.84	23.48	1.90	.80
1/16 inch and finer	8.6				
Very fine, decanted [a]	5.4			.49	.20
Remainder	3.2	17.13	4.48	.55	.14
				9.68	3.94
Washed at 1¼-inch size:					
Sample No. 1		8.94	3.33		
No. 2		8.18	3.36		

INDIANA NO. 9 B.

[Unwashed coal (boiler-test sample, No. 2035)—ash, 10.98; sulphur, 3.02.]

¼ inch to 1/16 inch	78.4				
Lighter than 1.35	64.2	8.04	2.30	5.16	1.48
1.35 to 1.65	7.3	25.90	4.60	1.89	.33
Heavier than 1.65	3.2	60.75	16.70	1.94	.52
1/16 inch and finer	21.3				
Very fine, decanted [a]	8.8			.97	.26
Remainder	12.5	19.87	4.24	2.48	.53
				12.44	3.12
Washed at 1¼-inch size:					
Sample No. 1		9.22	2.91		
No. 2		8.54	2.69		

[a] Estimated from results on unwashed coal.

Determinations of ash and sulphur in coal samples variously treated—Continued.

INDIANA NO. 11.

[Unwashed coal (boiler-test sample, No. 2421)—ash, 8.60; sulphur, 1.61.]

	Portion.	Ash.	Sulphur.	Compared with original sample.	
				Ash.	Sulphur.
¼ inch to 1/40 inch	80.9				
Lighter than 1.35	72.4	6.10	1.22	4.42	0.88
1.35 to 1.65	4.9	25.90	2.78	1.27	.14
Heavier than 1.65	3.4	54.34	10.14	1.85	.34
1/40 inch and finer	18.7				
Very fine, decanted [a]	9.7			.83	.16
Remainder	9.0	18.69	2.30	1.25	.21
				9.62	1.73

KENTUCKY NO. 6.

[Unwashed coal (boiler-test sample, No. 2662)—ash, 3.15; sulphur, 0.44.]

¼ inch to 1/40 inch	89.8				
Lighter than 1.35	88.4	2.27	0.56	2.01	0.50
1.35 to 1.65	.6	27.30	.71	.15	.00
Heavier than 1.65	.6	71.61	.85	.43	.01
1/40 inch and finer	9.8				
Very fine, decanted [a]	6.0			.19	.03
Remainder	3.9	6.85	.70	.27	.03
				3.05	.57

MISSOURI NO. 5.

[Unwashed (boiler-test sample, No. 2892)—ash, 16.94; sulphur, 5.60.]

¼ inch to 1/40 inch	91.5				
Lighter than 1.35	74.7	6.86	3.17	5.12	2.37
1.35 to 1.65	8.4	23.13	6.97	1.94	.59
Heavier than 1.65	9.4	55.85	16.28	5.25	1.53
1/40 inch and finer	8.2				
Very fine, decanted [a]	3.3			.57	.19
Remainder	4.9	25.30	6.73	1.24	.33
				14.12	5.01
Washed at 1¼-inch size:					
Sample No. 1		10.28	4.10		
No. 2		10.12	3.94		

MISSOURI NO. 6.

[Unwashed coal (boiler-test sample, No. 2927)—ash, 11.67; sulphur, 5.52.]

¼ inch to 1/40 inch	89.2				
Lighter than 1.35	79.6	6.96	3.69	5.54	2.94
1.35 to 1.65	7.0	21.08	8.33	1.48	.58
Heavier than 1.65	6.1	46.89	20.81	2.86	1.27
1/40 inch and finer	10.4				
Very fine, decanted [a]	2.0			.23	.11
Remainder	8.4	16.55	6.66	1.39	.56
				11.50	5.46

[a] Estimated from results on unwashed coal.

Determinations of ash and sulphur in coal samples variously treated—Continued.

OHIO NO. 1.

[Unwashed coal (boiler-test sample, No. 2136)—ash, 16.91; sulphur, 5.34.]

	Portion.	Ash.	Sulphur.	Compared with original sample.	
				Ash.	Sulphur.
⅛ inch to 1/16 inch	87.0				
Lighter than 1.35	57.5	5.97	2.91	3.43	1.67
1.35 to 1.65	16.8	18.91	5.87	3.18	.98
Heavier than 1.65	7.3	54.35	15.01	3.97	1.10
1/16 inch and finer	12.9				
Very fine, decanted [a]	7.3			1.23	.39
Remainder	5.7	29.56	7.04	1.69	.40
				13.50	4.54
Washed at 1¼-inch size:					
Sample No. 1		9.20	3.98		

OHIO NO. 5.

[Unwashed coal (boiler-test sample, No. 2101)—ash, 8.02; sulphur, 1.65.]

⅛ inch and 1/16 inch	90.8				
Lighter than 1.35	78.1	4.77	1.39	3.73	1.09
1.35 to 1.65	7.5	17.33	2.53	1.30	.19
Heavier than 1.65	3.4	69.67	3.72	2.37	.13
1/16 inch and finer	8.9				
Very fine, decanted [a]	6.4			.51	.10
Remainder	2.6	12.70	2.74	.33	.07
				8.24	1.58

PENNSYLVANIA NO. 8.

[Unwashed coal (boiler-test sample, No. 2446)—ash, 6.33; sulphur, 0.89.]

⅛ inch to 1/16 inch	78.5				
Lighter than 1.35	71.0	5.02	0.58	3.56	0.41
1.35 to 1.65	4.8	21.19	1.49	1.02	.07
Heavier than 1.65	1.6	51.98	8.36	.83	.13
1/16 inch and finer	21.2				
Very fine, decanted [a]	12.6			.80	.11
Remainder	8.6	7.51	1.10	.65	.09
				6.86	.81

PENNSYLVANIA NOS. 7 A AND 7 B.

[Unwashed coal (boiler-test sample, No. 2182)—ash, 11.36; sulphur, 1.68.]

⅛ inch to 1/16 inch	90.6				
Lighter than 1.35	73.5	8.81	1.40	6.48	1.03
1.35 to 1.65	14.6	23.12	2.03	3.38	.30
Heavier than 1.65	1.1	43.65	9.71	.48	.11
1/16 inch and finer	9.0				
Very fine, decanted [a]	7.4			.84	.13
Remainder	1.7	12.53	3.59	.21	.06
				11.39	1.63
Washed at 1¼-inch size:					
Sample No. 1		10.62	1.63		
No. 2		11.36	1.68		

[a] Estimated from results on unwashed coal.

Determinations of ash and sulphur in coal samples variously treated—Continued.

PENNSYLVANIA NO. 10.

[Unwashed coal (boiler-test sample, No. 2373)—ash, 6.37; sulphur, 1.35.]

	Portion.	Ash.	Sulphur.	Compared with original sample.	
				Ash.	Sulphur.
¼ inch to 1/20 inch	87.0				
Lighter than 1.35	78.5	4.50	1.07	3.53	0.85
1.35 to 1.65	5.6	13.15	1.84	.75	.10
Heavier than 1.65	1.9	62.70	8.70	1.19	.17
1/20 inch and finer	12.7				
Very fine, decanted [a]	7.6			.48	.11
Remainder	5.0	9.49	2.27	.48	.11
				6.43	1.34

TENNESSEE NO. 6.

[Unwashed coal (boiler-test sample, No. 3102)—ash, 14.86; sulphur, 0.80.]

¼ inch to 1/20 inch	93.8				
Lighter than 1.35	71.5	3.42	0.67	2.45	0.47
1.35 to 1.65	7.7	20.64	1.18	1.59	.09
Heavier than 1.65	14.0	70.99	2.74	9.94	.38
1/20 inch and finer	5.9				
Very fine, decanted [a]	2.7			.40	.02
Remainder	3.3	22.75	1.08	.75	.04
				15.13	1.00

VIRGINIA NO. 4.

[Unwashed coal (boiler-test sample, No. 2533)—ash, 4.02; sulphur, 0.45.]

¼ inch to 1/20 inch	92.8				
Lighter than 1.35	88.3	1.93	0.48	1.70	0.41
1.35 to 1.65	1.3	15.91	.95	.20	.01
Heavier than 1.65	2.6	72.22	.92	1.877	.02
1/20 inch and finer	6.8				
Very fine, decanted [a]	4.6			.18	.02
Remainder	2.3	10.24	.77	.24	.02
				4.19	.48

VIRGINIA NO. 2.

[Unwashed coal (boiler-test sample, No. 2557)—ash, 6.58; sulphur, 0.83.]

¼ inch to 1/20 inch	82.6				
Lighter than 1.35	71.2	2.74	0.69	1.95	0.49
1.35 to 1.65	9.0	16.57	1.35	1.49	.12
Heavier than 1.65	1.3	60.02	9.65	.78	.13
1/20 inch and finer	17.1				
Very fine, decanted [a]	12.6			.82	.10
Remainder	4.6	12.33	1.23	.57	.06
				5.61	.90
Washed at 1¼-inch size:					
Sample No. 1		4.15	.92		
No. 2		4.02	.95		
No. 3		4.55	.86		

[a] Estimated from results on unwashed coal.

Determinations of ash and sulphur in coal samples variously treated—Continued.

WEST VIRGINIA NO. 13.

[Unwashed coal (boiler-test sample, No. 2058)—ash, 3.93; sulphur, 0.96.]

	Portion.	Ash.	Sulphur.	Compared with original sample.	
				Ash.	Sulphur.
⅛ inch to 1/20 inch	93.6				
Lighter than 1.35	89.1	2.41	0.83	2.15	0.74
1.35 to 1.65	2.2	20.72	1.27	.46	.03
Heavier than 1.65	1.7	70.16	2.59	1.19	.04
1/20 inch and finer	6.1				
Very fine, decanted [a]	3.6			.14	.04
Remainder	2.5	9.64	1.08	.24	.03
				4.18	.88

WEST VIRGINIA NO. 14.

[Unwashed coal (boiler-test sample, No. 2052)—ash, 2.27; sulphur, 1.07.]

⅛ inch to 1/20 inch	88.6				
Lighter than 1.35	84.4	1.52	0.88	1.28	0.74
1.35 to 1.65	1.0	14.52	2.11	.15	.02
Heavier than 1 65	1.0	58.60	13.45	.59	.13
1/20 inch and finer	11.1				
Very fine, decanted [a]	7.7			.17	.08
Remainder	3.4	7.10	1.89	.24	.07
				2.43	1.04

WEST VIRGINIA NO. 18.

[Unwashed coal (boiler-test sample, No. 2607)—ash, 6.21; sulphur, 0.67.]

⅛ inch to 1/20 inch	91.0				
Lighter than 1.35	86.0	4.88	0.68	4.20	0.59
1.35 to 1.65	3.0	22.81	.50	.68	.02
Heavier than 1.65	1.0	62.55	.57	.63	.01
1/20 inch and finer	8.6				
Very fine, decanted [a]	6.1			.38	.04
Remainder	2.5	7.97	.83	.20	.02
				6.09	.68

WYOMING NO. 2 B.

[Unwashed coal (boiler-test sample, No. 2164)—ash, 21.38; sulphur, 4.41.]

⅛ inch to 1/20 inch	91.0				
Lighter than 1.35	62.1	10.85	4.34	6.77	2.70
1.35 to 1.65	21.4	31.84	3.27	6.81	.70
Heavier than 1.65	12.1	64.30	6.48	7.78	.78
1/20 inch and finer	5.9				
Very fine, decanted [a]	3.3			.71	.15
Remainder	2.6	31.45	4.41	.82	.11
				22.89	4.44

[a] Estimated from results on unwashed coal.

Determinations of ash and sulphur in coal samples variously treated—Continued.

SPECIAL TEST ON REFUSE FROM A WASHING.

[Original refuse—ash, 47.50; sulphur, 1.71.]

	Portion.	Ash.	Sulphur.	Compared with original sample.	
				Ash.	Sulphur.
¼ inch to $\frac{1}{16}$ inch	85.2				
Lighter than 1.35	15.0	12.23	0.88	1.83	0.13
1.35 to 1.65	17.7	28.13	.76	4.98	.13
Heavier than 1.65	51.4	64.88	1.79	33.35	.92
$\frac{1}{16}$ inch and finer	14.5				
Very fine, decanted[a]	3.0			1.43	.05
Remainder	11.6	33.27	1.48	3.83	.17
				45.42	1.40

[a] Estimated from results on original refuse.

VOLATILE MATTER IN COALS AND LIGNITES.[a]

The official method of determining volatile matter, recommended by the committee on coal analysis appointed by the American Chemical Society, is as follows:

Place 1 gram of fresh, undried, powdered coal in a platinum crucible weighing 20 or 30 grams and having a tightly fitting cover. Heat over the full flame of a Bunsen burner for seven minutes. The crucible should be supported on a platinum triangle, with the bottom 6 to 8 centimeters above the top of the burner. The flame should be fully 20 centimeters high when burning free, and the determination should be made in a place free from draughts. The upper surface of the cover should burn clear, but the under surface should remain covered with carbon. To find "volatile combustible matter," substract the per cent of moisture from the loss found here.

This method has been used regularly in the volatile determinations made in the laboratory, the only modification being that the flame is protected from air currents by inclosing the apparatus in a cylindrical asbestos shield 15 centimeters long and 7 centimeters in diameter, the platinum triangle being located 3 centimeters below the top of the shield. The use of the shield gives more uniformity in the heat treatment, with a corresponding greater uniformity of results.

In most coals the routine results obtained in the laboratory have checked to within less than 0.3 or 0.4 per cent; occasionally a sample has given trouble, and the variation between duplicates, without any apparent reason, was as great as 1 per cent. On some lignites it has been found impossible to obtain close duplicates, and on a few samples the official method gives very inaccurate determinations—as may be shown by the following results obtained in the laboratory upon two different samples, Nos. 2734 and 2764, of Texas No. 3 lignite, which differed only in the amount of moisture remaining in the air-dried sample, and perhaps in the fineness of grinding:

[a] By permission of Dr. J. A. Holmes, in charge, and the director of the laboratory, the results of this investigation of the volatile matter was published by Prof. E. E. Somermeier as a paper in the Journal of the American Chemical Society, August, 1906.

Laboratory analyses on samples 2734 and 2764 of Texas No. 3 lignite.

Constituent.	Samples.		
	2734.	2764.	
	1.	2.	3.
Moisture	9.88	20.24	20.24
Volatile matter	36.17	58.48	35.42
Fixed carbon	43.65	10.85	33.91
Ash	10.30	10.43	10.43
Sulphur	1.30	1.03	1.03

This great difference in the fixed-carbon results shown in columns 1 and 2 could not be accidental, as all of the determinations on both samples were duplicated. A series of determinations was begun, to learn, if possible, the cause of this great variation. The two following causes were suspected, both of which were found to be partly responsible for the difference: (1) Mechanical loss due to the throwing out of solid particles by the too rapid expulsion of the volatile matter. The possibility of loss from this source is mentioned in the report of the committee of the American Chemical Society, but the results of their experiments are negative. (2) A different breaking down of the hydrocarbon compounds when expelled under different conditions and in the presence of variable amounts of moisture.

The results of Mr. N. M. Austin's preliminary treatment of tne sample with a low heat and then with the application of the full flame of the Bunsen burner gives higher results in fixed carbon than where the full flame of the Bunsen burner is applied from the beginning. The proximate analysis of sample 2764, giving the unusual results, which was finally reported by the laboratory, is shown in column 3.

A series of seven results by the official method gave for volatile matter on this sample an average of 62.5 per cent, with a variation between high and low results of over 12 per cent. Three results of volatile matter on this sample made after previous expulsion of the moisture at 105° C. gave average volatile matter 39.6 per cent, with a variation between high and low results of 5.9 per cent. Preliminary treatment by driving off the moisture and most of the volatile matter at a low heat was then tried, the flame of the Bunsen burner being turned down to 10 centimeters and the crucible gradually heated. The application of the heat was regulated by holding the burner in the hand and heating in such a way as to expel the moisture slowly and gradually smoke off most of the volatile matter, the volatile matter escaping freely enough during the last minute of this preliminary heating to burn with a small flame around the edge of the crucible cover. Two results with five minutes of preliminary heating and then seven minutes over the full flame of the Bunsen burner gave an average in volatile matter of 35.08 per cent, the variation between the two results being 0.23 per cent. Two results with three minutes' pre-

liminary heating and seven minutes over the full flame of the Bunsen burner gave an average of 35.6 per cent, with a variation of 0.75 per cent between results. A result obtained by four minutes of preliminary heating and then seven minutes over the full flame gave 35.42 per cent. The difference in results obtained by the three-, four-, and five-minute preliminary treatment is small, and in all subsequent experimental tests the time of the preliminary heating was four minutes. To determine the mechanical losses and difference in volatile compounds given off, a number of ash determinations were made after the driving off of the volatile matter by the official method and after driving off the volatile matter in connection with the preliminary heating. The results of volatile matter and ash on three determinations by the official method and on two determinations by the modified method of four minutes of preliminary heating and then seven minutes over the full flame are as follows:

Determinations of volatile matter by two methods.

Constituent.	Official method.			Modified method.	
	1.	2.	3.	4.	5.
Volatile matter	66.72	67.47	54.82	36.06	36.65
Ash	4.30	4.38	[a] 7.25	11.16	11.15

[a] This result is possibly explained by the fact that this sample stood for two hours in the crucible after weighing out, and a considerable amount of the moisture content may have escaped before the sample was treated for the determination of the volatile matter.

That mechanical losses occurred during the rapid evolution of the volatile matter by the official method was also indicated by the shower of solid carbon particles driven off as sparks during the first few minutes, while with the preliminary heating these sparks were nearly or entirely absent. The average volatile matter on the first two determinations was 67.1 per cent, the average ash 4.34 per cent. The average volatile matter on the two results by the modified method was 36.35 per cent, ash 11.15 per cent. The moisture in the sample determined at this time was 19.78, giving fixed carbon 32.72 per cent. The difference in the ash results on the two pairs is 6.81 per cent, or the part of the ash driven off mechanically by the regular method is 6.81 ÷ 11.15, or 61 per cent. Taking this portion of the fixed-carbon result by the modified method gives 20 per cent as the amount of fixed carbon expelled mechanically in the first determinations. The results by the official method after making this correction, and also after taking the correct ash value, are shown in column 1 of the table below.

After making this correction for mechanical losses the difference in the fixed carbon by the two processes is still 10.75 per cent, which difference must be due to the difference in the breaking down of the hydrocarbon compounds by the different heat treatment. The ash

from the third result by the official method was 7.25 per cent, or the loss of ash 3.9 per cent. Correction for fixed carbon mechanically carried off is accordingly 3.9÷11.15, or 35 per cent. This portion of the fixed carbon as shown by the modified method gives 11.4 per cent as the amount of fixed carbon expelled mechanically. The result, after making the fixed-carbon and ash corrections, is shown in column 2 of the following table:

Corrected determinations by the official method.

Constituent.	Corrected results.	
	1.	2.
Moisture	19.78	19.78
Volatile matter	47.10	43.42
Fixed carbon	21.97	25.65
Ash	11.15	11.15
	100.00	100.00

The difference in this case in fixed carbon, due to the different heat treatment, is 7.07 per cent.

This particular sample was very finely ground. To find out how much the difference in result was due to the fineness of grinding a duplicate portion of the same sample was ground down till it passed a 40-mesh sieve. The results of duplicates by the official method and by the modified method are shown in the next table. The proximate analysis of the first sample by the modified method is shown in column 2. The correction for fixed carbon to be applied to the result of the official method is 0.95÷11.20, or 8.5 per cent of the fixed-carbon result of the modified method, which is 2.9 per cent. The results by the official method, after correcting for mechanical loss of fixed carbon and ash, are shown in column 1. The difference in fixed carbon between the two methods, due to different heat treatment, is 3.45 per cent. These results show, at least for lignites, that the fineness of the sample has an important effect. Upon a second sample of lignite, similar to the first except that it contained more moisture (30.45 per cent), the average results by the modified process are as tabulated in column 4. A comparison of the results in volatile matter and ash by the official method shows that the correction to be applied to the fixed carbon and ash for mechanical loss is 2.71÷10.83. These corrections, as applied to the results obtained by the official method, are shown in column 3.

Determinations on sample ground to pass a 40-mesh sieve.

Constituent.	First sample.		Second sample.	
	Official method.	Modified method.	Official method.	Modified method.
	1.	2.	3.	4.
Volatile matter	42.07	35.72	44.40	30.97
Ash	10.25	11.20	8.12	10.83
Loss in ash	.95	.....	2.71	.....
Proximate analysis:				
Moisture	[a] 19.35	19.35	[a] 30.45	30.45
Volatile matter	[a] 39.17	35.72	[a] 37.43	30.97
Fixed carbon	[a] 30.28	33.73	[a] 21.29	27.75
Ash	[a] 11.20	11.20	[a] 10.83	10.83
	100.00	100.00	100.00	100.00

[a] After correcting for mechanical loss of fixed carbon and ash, the difference in the fixed-carbon results between the two samples, due to different heat treatment, is 6.46 per cent.

To test the effect of the fineness of grinding upon the determination of the volatile matter in ordinary bituminous coal, a sample of coal, Kentucky No. 1 C, containing 2 per cent moisture, 5.7 per cent ash, and 0.9 per cent sulphur, was still further reduced in ash content by floating on a calcium-chloride solution of 1.32 specific gravity. The lighter portion was then thoroughly air dried and separated by sifting into five sizes, and proximate analyses of the parts were made by the official method, with the following results:

Determinations for volatile matter on Kentucky No. 1 C coal.

Constituent.	Sizes of separation by sifting.				
	$\frac{1}{4}$ to $\frac{1}{10}$	$\frac{1}{10}$ to $\frac{1}{20}$	$\frac{1}{20}$ to $\frac{1}{40}$	$\frac{1}{40}$ to $\frac{1}{80}$	$\frac{1}{80}$ and finer.
Moisture	1.15	1.45	1.70	1.90	2.05
Volatile matter	39.05	38.80	38.55	38.05	35.54
Fixed carbon	58.20	58.55	58.35	58.40	59.66
Ash	1.60	1.20	1.40	1.65	2.75

By the modified process with four minutes of preliminary heating the result in volatile matter on the "$\frac{1}{20}$ to $\frac{1}{40}$" size was 33.75 per cent and on the "$\frac{1}{80}$ and finer," 32.85 per cent.

The results in volatile matter on these different sizes are somewhat higher on the coarse samples. However, the different ash contents of the different sizes indicate that the sizing had to a degree separated the coal into somewhat different varieties, as the higher ash content of the finer sample would not in itself be sufficient to account for the lower volatile results. In order to see whether the difference was due to the fineness of grinding or difference in the coals, a portion of the "$\frac{1}{20}$ to $\frac{1}{40}$" sample was ground down in an agate mortar and the volatile matter determined on this fine portion. The average of several results was 37.6 per cent, as against 38.55 per cent on the coarse sample.

From this series of results it appears, at least in low-moisture bituminous coals, that the finer ground samples give somewhat lower

volatile matter than the coarser samples, probably due to the more complete sintering together of the fine samples upon heating, with the consequent effect upon the giving off of the volatile matter.

In order to find out how much effect different heat treatment has on different fuels, a series of samples was selected ranging from anthracite to peat, most of the samples used in the tests having been previously more or less completely air dried so as to permit of better handling in the laboratory. Determinations for volatile matter were made in duplicate by the regular official method and by the modified method with four minutes' preliminary heating. The proximate analyses of the samples with the volatile matter determined by the official method are shown in columns 1 to 5 of the next table; the results for volatile matter by the preliminary heating are given in column 6; and the differences in volatile matter by the two methods are given in column 7. The determinations for moisture were all made in accordance with the official method, by weighing out a separate sample. The same is true of the determinations for ash, with the exception that upon two or three of the lignite samples and one of the Pennsylvania samples the results for ash are those obtained after the determination of the volatile matter by the modified process. These particular samples and results are all specifically mentioned elsewhere (p. 42).

Effect of different heat treatment on determination of volatile matter.

Fuel treated.	Proximate analysis (official method).					Volatile matter (modified method.)	Difference.
	Moisture.	Volatile matter.	Fixed carbon.	Ash.	Sulphur.		
	1.	2.	3.	4.	5.	6.	7.
Colorado anthracite	2.80	5.05	77.55	14.60	0.60	4.90	0.15
Arkansas	.83	12.47	72.05	14.65	2.14	12.37	.10
Pennsylvania	.90	17.35	74.92	6.83	.97	16.07	1.28
Do	1.05	33.10	53.30	12.55	1.76	30.35	2.75
Kentucky	2.99	37.51	56.68	2.82	.58	34.78	2.73
Indiana	4.20	37.70	45.65	12.45	4.13	34.67	3.03
Washington	6.65	35.87	44.57	12.91	.68	34.25	1.62
Indiana	8.40	34.40	48.72	8.48	1.47	32.00	2.40
North Dakota lignite	11.65	45.58	32.97	9.80	1.04	40.17	5.41
Illinois	12.40	32.18	42.82	12.60	1.30	30.12	2.06
Texas lignite (fine)	19.78	62.50	6.57	11.15	1.03	[a] 35.42	27.08
Texas lignite (40-mesh duplicate)	19.35	42.07	27.38	11.20	.....	35.72	6.35
Texas lignite (not air dried)	30.45	44.40	15.42	9.73	.....	30.97	13.43
Massachusetts peat	13.25	49.80	16.21	20.74	.58	47.92	1.88

[a] Two determinations upon the fine sample of Texas lignite made by heating for four minutes over a flame 5 centimeters high and then seven minutes over the full flame (25 cm.) gave 35.47 per cent volatile matter—almost an exact check upon the result obtained by the four-minute preliminary heating with a 10-centimeter flame regulated by holding burner in the hand.

With the exception of the anthracite and semianthracite samples, the results by the preliminary heating, as compared with those by the official method, all show a considerably less amount of volatile matter and a correspondingly greater amount of fixed carbon. In the case of the lignites, the greater volatile matter by the official method, as has been shown, is partly due to mechanical losses.

In order to see if mechanical losses might account for the differences on the bituminous coals, determinations for the ash after the determination of the volatile matter were made on one of the Pennsylvania samples. The average results for ash on the samples by the two methods are: Official method, 12.56; preliminary heating, 12.53. These results indicate no mechanical loss whatever, and in none of the samples except the lignites were visible solid carbon particles driven off in the form of sparks, and the differences must be ascribed to the different breaking down of the hydrocarbon compounds by the difference in heat treatment.

Comparisons of the results of volatile matter on a great number of samples differing from one another in moisture content indicate that the presence of loosely held moisture in the sample causes a higher volatile result. In order to obtain more definite data on this question, three samples low in moisture and representing widely different kinds of coal were selected for a series of determinations. The effect of loosely held moisture upon the determinations for volatile matter in each of these samples was determined by adding definite amounts of water to the sample after weighing out. The water was thoroughly mixed with the sample by means of a fine platinum wire and the volatile determination then made in the usual manner according to the official method. The first sample selected was a sample of Pennsylvania coal. The proximate analysis of the air-dried sample and the results for volatile matter determined in the presence of additional moisture are shown in the next table. Air-dried samples of Illinois coal and Arkansas lignite were treated in the same way, with the results also shown in the table.

Determinations of volatile matter (percentages) showing effect of loosely held moisture.

Fuel treated.	Proximate analysis (official method).					Volatile-matter determinations in the presence of stated amounts of added moisture.					
	Moisture.	Volatile matter.	Fixed carbon.	Ash.	Sulphur.	0.03 gram.	0.05 gram.	0.1 gram.	0.15 gram.	0.2 gram.	0.3 gram.
Pennsylvania coal	1.05	33.00	53.30	12.55	1.75	.....	33.60	33.70	33.80	34.10	33.90
Illinois coal	2.35	39.35	44.65	13.65	.....	39.60	39.30	40.00	40.05	39.75	.....
Arkansas lignite	10.85	38.50	31.40	19.25	.83	.....	40.35	41.20	40.90	44.90	.....

Without exception these results show that the presence of loosely held moisture in the sample increases the value obtained for the volatile combustible matter. The average increase for the Pennsylvania sample is about 0.7 per cent. On the Illinois sample the increase for volatile matter is 0.4 per cent. On the Arkansas lignite the increase is 3.3 per cent.

To see what effect this loosely held moisture might have on the volatile determinations where the sample was first subjected to four

minutes' preliminary heating over a low flame, determinations were made upon these samples with and without additional moisture, with the following results:

Determinations of volatile matter (percentages) after four minutes' preliminary heating, showing effect of loosely held moisture.

Fuel treated.	Volatile-matter determinations (by modified method) in the presence of stated amounts of added moisture.			
	No moisture added.	0.15 gram.	0.2 gram.	0.3 gram.
Pennsylvania coal	30.35	.....	.....	31.65
Illinois coal	34.85	36.10	.....	.....
Arkansas lignite	36.90	.....	37.40	.....

These results show that even with a gradual preliminary heating the presence of loosely held moisture increases the value of the volatile determinations, the difference in some of the samples being as great as the difference by the official method; from which it appears that the rapid application of heat sufficient to drive off this moisture results in a reaction between the water vapor and the carbon or hydrocarbons in the coal.

The results of the foregoing experiments and tests show that the value obtained for volatile matter in coal is affected to an important degree: (1) By the method of heating the sample, (2) by the fineness of pulverization, and (3) by the amount of loosely held moisture present. In bituminous coals these differences do not exceed 3 or 4 per cent, and appear to be entirely due to a different breaking up of the hydrocarbon compounds under the different conditions of heat treatment, fineness of sample, and amount of moisture present. In the case of lignites, where the difference may be as high as 25 per cent, this difference is largely due to the mechanical loss in the sample during the rapid expulsion of the volatile matter.

In the routine work of the laboratory in making the determinations of volatile matter the official method is at present used for ordinary bituminous coals, while lignites or other coals with more than 10 per cent moisture are heated for four minutes at a low temperature and then for seven minutes over the full flame of the Bunsen burner.

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Correspondence should be addressed to

THE DIRECTOR,
UNITED STATES GEOLOGICAL SURVEY,
WASHINGTON, D. C.

SEPTEMBER, 1907.

O

Bulletin No. 324 Series R, Structural Materials, 1

DEPARTMENT OF THE INTERIOR
UNITED STATES GEOLOGICAL SURVEY
GEORGE OTIS SMITH, DIRECTOR

THE SAN FRANCISCO EARTHQUAKE AND FIRE OF APRIL 18, 1906

AND THEIR EFFECTS ON STRUCTURES AND STRUCTURAL MATERIALS

REPORTS BY

GROVE KARL GILBERT, RICHARD LEWIS HUMPHREY,
JOHN STEPHEN SEWELL, AND FRANK SOULÉ

WITH PREFACE BY

JOSEPH AUSTIN HOLMES
In Charge of Technologic Branch

WASHINGTON
GOVERNMENT PRINTING OFFICE
1907

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B 35. Physical properties of the iron carburets, by Carl Barus and Vencent Strouhal. 1886. 62 pp.

B 36. Subsidence of fine solid particles in liquids, by Carl Barus. 1886. 58 pp. (Out of stock.)

B 42. Report of work done in the Division of Chemistry and Physics, mainly during the fiscal year 1885–86, by F. W. Clarke. 1887. 152 pp., 1 pl. (Out of stock.)

B 47. Analyses of waters of the Yellowstone National Park, with an account of the methods of analyses employed, by F. A. Gooch and J. E. Whitfield. 1888. 84 pp. (Out of stock.)

B 52. Subaerial decay of rocks and origin of the red color of certain formations, by I. C. Russell. 1889. 65 pp., 5 pls. (Out of stock.)

B 54. On the thermoelectric measurement of high temperatures, by Carl Barus. 1889. 313 pp., 11 pls. (Out of stock.)

B 55. Report of work done in the Division of Chemistry and Physics, mainly during the fiscal year 1886–87, by F. W. Clarke. 1889. 96 pp. (Out of stock.)

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PREFACE.

By Joseph A. Holmes.

Immediately after the San Francisco earthquake and fire of April 18, 1906, it was decided to arrange for an investigation of their effects on buildings and materials of construction. Accordingly, on April 19 Richard L. Humphrey was sent to San Francisco for this purpose, as secretary of the National Advisory Board on Fuels and Structural Materials and representing the structural materials division of the United States Geological Survey. At the request of the President, Capt. John Stephen Sewell, Corps of Engineers, United States Army, was sent to San Francisco on a similar errand by the War Department under order of April 23, 1906. Frank Soulé, dean of the college of civil engineering of the University of California, was asked late in the fall of 1906 to prepare a report on the general earthquake and fire conditions. G. K. Gilbert, of the United States Geological Survey, also a member of the California earthquake investigation commission, who was near San Francisco at the time of the disaster, was asked to prepare a brief special report on the phenomena of the earthquake.

Mr. Gilbert has brought into his paper only the salient features and results of the earthquake, for the reason that the subject is being treated more fully in the report of the California earthquake investigation commission.

Mr. Humphrey, who during the last two years has had charge of the structural materials laboratories of the United States Geological Survey, has had many years' experience in the investigation of structural materials, especially with regard to their fire-resisting qualities.

Before going to San Francisco Captain Sewell had studied carefully the effects of fire on buildings and materials, especially as indicated by the results of the conflagration at Baltimore in 1904.

Professor Soulé has had the advantage not only of a large experience, but also of being thoroughly familiar with the conditions in San Francisco prior to the earthquake and fire, and of being on the ground during their occurrence. He has had subsequently every opportunity for studying, at first hand and in great detail, the effects of both the earthquake and the fire.

The investigations of these three engineers were conducted independently, and their reports have been prepared without collaboration. Under these circumstances there are necessarily some differences of opinion as to matters of detail, but as to the more important features the writers are in hearty accord. About four hundred illustrations were submitted with the original reports; many of these do not appear with the printed reports because their use would have involved duplication, but wherever a view given by one author was rejected because of its similarity to a view by another author showing the same engineering features, a reference to the accepted view has been inserted. The legend appended to each illustration indicates whether the original view was actually taken by the author or was procured from another source.

Persons interested in this subject are advised not only to read each of these papers, but also to consult a number of other important papers on this subject which have appeared in the different technical journals and the proceedings of technical societies during the last several months. (See list at end of bulletin, pp. 159–161.)

THE SAN FRANCISCO EARTHQUAKE AND FIRE OF APRIL 18, 1906, AND THEIR EFFECTS ON STRUCTURES AND STRUCTURAL MATERIALS.

By G. K. Gilbert, R. L. Humphrey, J. S. Sewell, and Frank Soulé.

THE EARTHQUAKE AS A NATURAL PHENOMENON.

By G. K. Gilbert.

INTRODUCTION.

The investigations to which the San Francisco earthquake has given rise are of two classes—the study of the natural phenomena constituting or associated with the earthquake, and the study of the relations of the San Francisco earthquake and future earthquakes to human activities.

The principal studies of the earthquake as a natural phenomenon are under the direction of the California earthquake investigation commission, which was appointed by the governor of the State three days after the occurrence of the shock. The human or economic aspects of the subject have been studied chiefly by engineers and architects, of whom a number have acted in private capacity, while others have acted as the representatives of governmental or private organizations. In many of the architectural studies the earthquake and fire have been considered together, as the destructive effects of these two sources of danger were closely associated in the San Francisco disaster.

This volume is devoted to certain economic aspects of the subject, and the present chapter on natural phenomena of the earthquake selects those features which seem contributory to an understanding of the papers which follow. A fuller account of the earthquake may be found in the preliminary report of the State commission

above referred to; and a monographic report is to be expected when the labors of this commission shall have been completed.[a]

An earthquake is a jar occasioned by some violent rupture. Sometimes the rupture results from an explosion, but more commonly from the sudden breaking of rock under strain. The strain may be caused by the rising of lava in a volcano or by the forces that make mountain ranges and continents. The San Francisco earthquake of April 18, 1906, had its origin in a rupture associated with mountain-making forces. A rupture of this sort may be a mere pulling apart of the rocks so as to make a crack, but examples of that simple type are comparatively rare. The great majority of ruptures include not only the making of a crack but the relative movement or sliding of the rock masses on the two sides of the crack; that is to say, instead of a mere fracture there is a geologic fault. After a fault has been made its walls slowly become cemented or welded together; but for a long time it remains a plane of weakness, so that subsequent strains are apt to be relieved by renewed slipping on the same plane of rupture, and hundreds of earthquakes may thus originate in the same place.

A faulting may occur far beneath the surface and be known only through the resulting earthquake; but some of the quake-causing ruptures extend to the surface, and thus become visible. The New Madrid and Charleston earthquakes are examples of those having deep-seated origins; the shocks at Inyo and San Francisco, of those whose causative faults reached the surface of the ground.

The San Francisco earthquake had its origin, wholly or chiefly, in a new slipping on the plane of an old fault. The trend of the fault is northwest and southeast, and it is known through a distance of several hundred miles. Visible evidence of fresh slipping—a surface trace, to be described presently—does not appear through its whole extent, but has been traced from San Juan at the south to Point Arena at the north (fig. 1), a distance of about 180 miles. Because the earthquake was severe in Priest Valley, 60 miles southeast of San Juan, it is thought that subterranean slipping on the old fault plane extended beyond San Juan. At Point Arena the visible fault trace passes under the ocean, and the line of its trend does not again touch the coast, so that its northwestern course and extent are in doubt. A fault trace which appears at Point Delgada, 75 miles to the north, may be part of its continuation or may represent a separate fracture. In a general way the intensity of the shock was greatest near the

[a] The California earthquake investigation commission is composed of Andrew C. Lawson (chairman), A. O. Leuschner (secretary), G. K. Gilbert, H. F. Reid, J. C. Branner, George Davidson, Charles Burkhalter, and W. W. Campbell. Its work is organized under three committees—a committee on isoseismals, A. C. Lawson, chairman; a committee on coseismals, A. O. Leuschner, chairman, and a committee on the geophysics of the earthquake, H. F. Reid, chairman.

fault trace and diminished with distance therefrom; but to this rule there are important exceptions, and it has been noted especially

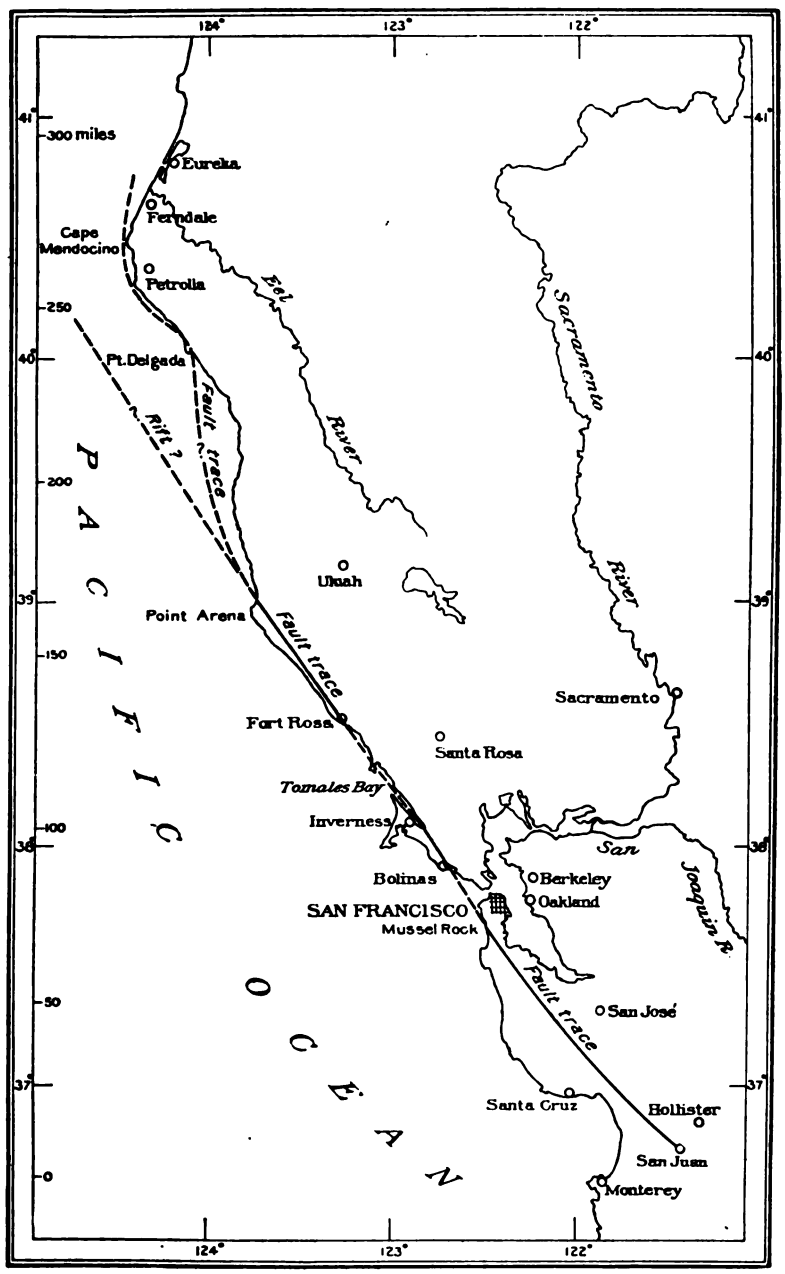

FIG. 1.—Map of the fault trace. Broken lines indicate alternative hypotheses as to its extension north of Point Arena.

that an area of high intensity coincided approximately with the Santa Rosa Valley, which trends northwestward, parallel to the main

fault. As the ridges of the neighboring Coast Range have the same northwesterly trend, it is thought probable that a subterranean slipping here occurred on a fault associated with the valley. In that case the geologic event causing the earthquake included coincident or nearly coincident yielding on more than one fault plane of the Coast Range system, and various other peculiarities in the distribution of intensity may be ascribed to local faulting.

The region of high intensity, to which most of the destruction was limited, is a belt 20 to 40 miles wide, extending from the mouth of Eel River at the northwest to Priest Valley at the southeast (fig. 1). This belt includes the surface expression of the principal fault—a feature distinctively known as the fault trace—a large number of cracks, and many local and superficial dislocations of soil and rock variously characterized as landslides and slumps.

THE FAULT TRACE.

The plane of the earthquake-causing fault, where it appears at the surface, is approximately vertical. The movement which took place along this plane was approximately horizontal.

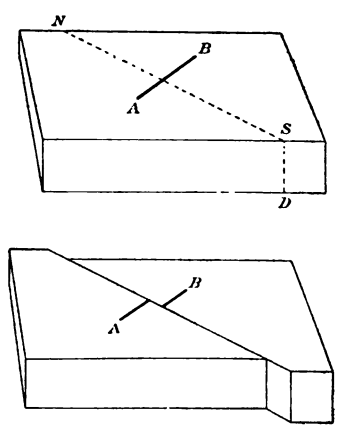

FIG. 2.—Diagrams illustrating the nature of the earthquake-making fault.

As the statement of these relations is sometimes found confusing, they are here illustrated diagrammatically. The upper diagram in fig. 2 represents a rectangular block as if cut from the land, the thickness being 25 feet, the length east and west (right to left) 150 feet, and the width 100 feet. The dotted line NS indicates the surface outcrop of the old fault plane, trending northwest and southeast, this plane cutting the face of the block in the vertical line SD. AB stands for any straight line on the surface of the land—such as would be defined by a road, a fence, or a row of trees—crossing the fault outcrop at right angles. The lower diagram represents the same

rectangular block after the earthquake, its two parts dislocated by sliding horizontally along the fault plane, and the line AB made discontinuous by an offset.

To return, now, from the ideal to the actual, the sides and bottom of the earth block disappear. The depth to which the fault penetrates is indefinite and unknown, and so is the extent of the lands on either side affected by the displacement. For nearly 200 miles there is a fracture on the face of the land, and everything traversed by the fracture is dislocated, the part on the southwest side having apparently moved toward the northwest and the part on the northeast side having apparently moved toward the southeast. The total horizontal offset ranges in general from 2 to 16 feet, but at one place, affected by abnormal conditions, reaches 20 feet (Pl. I, *A*). The effect is also shown by a redwood tree (Pl. II), which was situated at a place where the displacement was slight. The average offset is 10 to 12 feet. Associated with the horizontal dislocation are vertical dislocations of minor and variable amount. This line of fracture, with the associated dislocation, is the surface expression of the fault which occurred on April 18, 1906. It is the visible trace of the fault across the surface of the land, and in the following pages will be called the "fault trace."[a]

The fault trace itself is in some places inconspicuous, as in the flat meadow represented in Pl. I, *B*, where one might readily walk across it without noticing that the ground had been disturbed. Its ordinary phase, however, includes a disruption of the ground suggestive of a huge furrow, consisting of a zone, between rough walls of earth, in which the ground is splintered and the fragments are dislocated and twisted. This phase is shown in Pl. III. In many places the fault trace sends branching cracks into bordering land, and locally its effect in dislocation is divided among parallel branches.

The views of the fault trace given in Pl. VII represent it at a point not far from the head of Tomales Bay, where it traverses a hillside having a general slope toward the southwest. In the upper view we look toward the northwest; in the lower, toward the south-southeast. The horizontal displacement is here about 16 feet, the ground at the left, in each view, having moved from us, and the

[a] In the case of an earthquake fault with important vertical displacement the surface expression is a small cliff or scarp, and to such a feature the name "fault scarp" has been given; but this name does not serve to characterize the feature produced by the horizontal displacement of April 18, 1906. In default of an appropriate and established name the geologists who first traced the feature made tentative use of "furrow" and "rift;" and the word rift was employed in the preliminary report of the California commission, in a popular article by the present writer, and probably in other places. The commission, however, in giving more deliberate attention to terminology, has determined to reserve the word rift for a meaning more in consonance with earlier geologic usage and to substitute "fault trace" for the surface expression of the fault. The present paper conforms to the nomenclature accepted by the commission.

[illegible] There is also a vertical displacement, the ground on the southwest side having been relatively lifted 1 or 2 feet, and the expression of the vertical change is exaggerated in the [illegible] view by the relation of the horizontal change to the local slope of the hillside. There is nothing in the pictures to show the amount or even the direction of the horizontal displacement, but measurements were made at neighboring points where the fault trace intersects a road, a trail, and a small gully. The nature of the evidence as to displacement is illustrated by Pl. I, *B*, which shows a dislocated fence. The locality is on the farm of E. R. Strain, near the head of Bolinas Lagoon, and the camera was directed toward the northeast at right angles to the trend of the fault trace. The main branch of the fault trace (which is here divided) crosses the foreground from left to right, touching the dissevered ends of the fence, but the shear is at this point so smooth that its surface trace is concealed by the grass. The fence, which before the earthquake was straight and continuous, was broken across and offset to the distance of 24 feet.

Between Point Arena and Fort Ross the course of the fault trace [illegible] is approximately parallel to the coast, passing to the [illegible] of all the coastal towns. From Fort Ross to the head of Tomales Bay it traverses the water, except at Bodega Bay and Preston Point, where for [illegible] it crosses the land. It again enters the water at Bolinas Lagoon, passing several miles outside the Golden [illegible] Mussel Rock, whence it follows a [illegible] which any large town. [illegible] Plantation post-office, Fort [illegible] Arena, Woodville, Boli- [illegible] San Juan.

[illegible] respectively, the [illegible]

CRACKS.

All through the area of high intensity cracks were made, and these were specially numerous near the fault trace. The cracks were also more numerous in soft alluvium than in hard ground, but the number which deeply penetrated the bed rock was large. Perhaps this feature is better expressed by saying that the bed rock was generally and profoundly shattered, but without important dislocation except on the old fault plane. The wide prevalence of shattering is shown by the derangement of the underground circulation of water. In every farming district within the main earthquake belt persons familiar with the springs noted changes in the flow of water, ranging from moderate diminution or increase to complete stoppage or to the breaking out of new springs. In some places the derangements were temporary only, but more commonly a permanent change was reported.

At the surface the cracks had great variety of expression. Some were barely perceptible as partings; others gaped so widely that one might look down them several yards. Some were mere pullings apart; others showed small differential movements of the nature of faulting. Some were solitary; others, especially those exhibiting faulting, were in groups. Some straggled and branched irregularly; others were nearly straight for hundreds of feet. Theoretically, some cracks were primary as regards the earthquake and others secondary; that is to say, some were caused directly by the preexistent stresses which produced the main fault and others were caused by the waves constituting the earthquake.

Pl. IV shows two types of secondary cracks. In *A* the cracks are crooked and without faulting. They traverse tidal mud near the head of Bolinas Lagoon and are near the main branch of the fault trace, which follows the base of the bluff seen at the right. The cracks seen in *B* are in Bolinas, within half a mile of the supposed position of the fault trace. The greater part of the village lies in a narrow valley dividing a plateau. The valley floor is of alluvium, the surface of which curves upward at the sides. As a result of the earthquake the alluvium settled somewhat toward the middle of the valley, thus forming along the bases of the hills a system of cracks associated with faulting.

DISLOCATIONS OF SURFACE MATERIAL.

The district most strongly affected by the earthquake is one in which landslips are normally of frequent occurrence. On many hill slopes were masses of earth or rock, the descent of which was sure to take place whenever conditions became favorable. The shaking of

the earth on the morning of April 18, 1906, supplied the lacking factor, and they were all loosened at once. In the simplest case, a poised rock toppled over and rolled down a slope. In other cases adhesion was overcome, with resultant sliding. In yet others strains occasioned by the sapping of cliffs were reinforced by kinetic strains and cohesion was overcome, with resultant fracture. Elsewhere an unconsolidated formation, even though in a dry condition, was made to flow by simple agitation. Hillside bogs and other bodies of wet earth lost coherence and flowed as mud. Slips of this character grade into those of wet alluvium or "made ground" resting upon gentle slopes—ground which under ordinary conditions flows or creeps at an almost imperceptible rate, but which by shaking was made to move several feet or yards in a few seconds. The filled districts of San Francisco afford several examples, and two of these are illustrated by Pls. V and VI, *B*. The view shown in Pl. V is northwestward on Ninth street, near Brannan. Before the earthquake the car tracks and curb line were straight and approximately level, and this condition was not disturbed on the relatively firm ground shown in the distance. In the nearer part of the view the street crosses a tract of made ground created by filling a valley tributary to a narrow tidal inlet called Mission Creek. The descent of this valley was southwestward, and the made ground flowed in that direction, carrying street and buildings with it. In taking the photograph reproduced in Pl. VI, *B*, the camera stood on ground made by the filling of Mission Lagoon, an expansion of Mission Creek, and was pointed northward, commanding a portion of Howard street. The made ground here flowed northeastward and the buckling of street-car tracks was caused by its motion. Where the same earth flow crossed Valencia street the horizontal movement amounted to 6 feet.

In the various cases of dislocation enumerated the motive force appeared to be gravity, and the apparent function of the earthquake was to initiate movement by overcoming equilibrium, adhesion, or cohesion, or else to increase mobility by agitation, and thereby temporarily convert a quasi solid into a quasi liquid. While I do not doubt that this explanation is ordinarily adequate, there is at least one dislocation of surface material for which it is inadequate, and this raises the question whether in various other instances it may not require qualification. I refer to an extensive shifting of mud on the bottom of Tomales Bay. At the head of the bay and thence for a distance of several miles northwestward the soft mud was moved bodily westward. It not only descended from the northeast shore, so as to cause deeper water, but ascended toward the southwest shore, creating a broad shoal (Pl. VII). The horizontal change of position near the southwest shore was in places more than 25 feet, and

the vertical change as much as 2 feet. As the ascending movement can not be ascribed to gravity, it must be referred to the earthquake, even though the way in which the earth waves produced the effect is not evident. The locality is adjacent to the fault trace, the position of which is along the bottom of the bay, east of the shoal.

The illustrations may require a few words of explanation. The upper view of Pl. VII looks northward from the southwest shore of the bay. Tide being low, the newly formed shoal or mud bank is broadly exposed, but the receding tide has left a lane of water to mark the separation of the mud bank from the firmer ground that withstood the quaking. Immediately after the earthquake the mud was rigid, as in the tract shown in Pl. VIII, *A*; but before the view of Pl. VII, *A*, was taken (April 28, 1906) the surface had been largely smoothed by the action of wind waves. A single ridge which escaped that action appears at the left in the upper view of Pl. VII and in the foreground of the lower view.

A permanent disturbance of the ground also resulted in many instances from compacting. Just as sand or grain that has been poured into a measure can be made by shaking to settle down and occupy less space, so various loose formations, and especially artificial fillings, were shaken together by the earthquake and the ground surface lowered. In such compacting the particles making up the aggregate are readjusted so as to fit more closely together and the voids are reduced. In dry formations compacted by the earthquake the reduction of voids was opposed only by the elasticity of the contained air. In wet formations it encountered the effectual resistance of the contained water, and could be accomplished only by the extravasation of some of the water. Ordinarily it was impossible to measure the settling due to compacting, or even to determine its occurrence as a phenomenon independent of ground flow, but it was clearly seen in various localities in San Francisco where those parts of graded streets which retained their simple shapes and straight lines served as reference planes for neighboring parts that were disturbed. (Compare the distance and foreground of Pl. V. Another example of the effect on the filled-in land in this part of the city is shown in Pl. VI, *A*, a view of Dore street between Bryant and Brannan streets. The settling of the soft ground caused the street to drop at least 5 feet at this place.)

The only notable water waves generated by the shock were in Tomales Bay, where a group of waves estimated to be 6 or 8 feet high came to the northeast shore. The automatic tide gage at the Presidio showed a depression of about 4 inches, with subsequent oscillations of similar amount. Water was spilled from tanks, etc., and in at least one place was thrown from a pool out on the land.

MOTIONS CONSTITUTING THE EARTHQUAKE.

The earthquake occurred between 10 and 15 minutes after 5 o'clock a. m., standard time of the one hundred and twentieth meridian. As time was consumed in the propagation of the shocks, the moment of beginning at any place depended in part on the distance of the place from the zone in which the disturbance originated. As this zone was hundreds of miles in extent it is probable that the time of beginning was not the same at all points along it. For similar reasons the character and sequence of the motions constituting the earthquake were not the same at any two localities, and the differences in the vicinity of the zone of origin may have been very great. In and near San Francisco the principal part had a duration of about one minute; it was preceded by comparatively faint tremors for several seconds, and it was followed by minor tremors. During the stronger part the motion was chiefly in horizontal directions and oscillatory, but its rhythm was irregular in period and emphasis. On firm ground in the same region the range of motion is believed to have been more than 2 inches, but was not measured, there being no seismograph capable of recording it. On soft ground the range of oscillatory motion may have been several times greater, and it was also greater in the immediate vicinity of the fault trace.

The following paragraphs present my conception of the essential character of the motions constituting the earthquake in the region of its destructive intensity. In the endeavor to make a brief and clear statement the conception is expressed somewhat badly, with little reference to the various uncertainties of fact and theory by which it is actually qualified.

The earthquake fault has a length of 300 miles, possibly 400. Nothing is known of its depth. It coincides with a plane of earlier faulting, on portions of which there have been movements within a few decades. The fact of recurrence on the same plane shows that the rock faces in contact had not become welded, so that the molecular force which there resisted motion was less than the cohesion of solid rock and may have been little stronger than adhesion. A tract of the crust including the fault plane had come to be affected by a system of slowly increasing shearing strains, and the associated stresses were the forces directly causing the fault. When the stress component coincident with the fault plane at some point became greater than the adhesion (or cohesion) a local slipping took place. This caused a redistribution of strains and stresses, the local relief of strain being followed by increase of strain and stress in all adjoining tracts of the fault plane, with the result that the adhesion was overcome in those tracts and the area of incipient faulting thereby enlarged. Thus from the initial tract the lesion was propagated as a sort of wave through all the fault plane.

At the initial tract a small movement sufficed to relieve the local strain, and the motion was then arrested by friction, but the movement was renewed by reaction from other tracts, and it alternately started and stopped till the accumulated stresses had spent themselves. There was a similar rhythmic sequence in other parts of the fault, the frequency of the alternations depending on local conditions; and the total movement of dislocation at each point was accomplished by a series of steps and not by a single leap.

The time consumed in these reactions was not infinitesimal. The rate of propagation of changes in strain was of the same order of magnitude as that of earthquake waves in general, and the rate of propagation of the initiation of movement on the old fault plane may have been somewhat slower because of the necessity of accumulating a certain amount of stress increment to overcome the adhesion. It is probable that the completion of the fault required more than one minute, and it may have required more than two minutes. It is even possible that the displacement had been completed at the initial point before it began at the most remote.

In the succession of slippings and stoppings at any point of the fault plane each separate slip communicated a jar or pulse to the surrounding rock, and this pulse was propagated in all directions. The earthquake at any locality in the neighborhood of the fault consisted of such pulses from different directions. The general distribution of intensity indicates that the pulses weakened in transmission somewhat rapidly, whence it may be inferred that the particular pulses constituting the dominant elements of the local earthquake were those from the nearer parts of the fault.

If this conception of the earthquake is correct, the rhythm observed in the region of high intensity was a phenomenon distinct from the rhythm of harmonic waves. It was essentially a frictional rhythm, dependent on the relation of certain rock strains and rock stresses to the resistances afforded by adhesion and sliding friction. It was irregular not only because the intervals of local starting and stopping were unequal, but because it was derived from a considerable area of the fault surface, in which the local rhythms were neither harmonious nor synchronous.

The compounding of unevenly spaced pulses from different points of the fault plane caused both reinforcement and interference, introducing a character analogous to beats in music, but without the regularity of musical beats. It also at times made oscillatory motions swifter in one direction than the other, so that reciprocative accelerations were not always symmetrically arranged. In less technical language, the motion was jerky and included abrupt phases that were almost blows. The compounding also introduced variety in the direction of motion, especially at the end, when for a short time the

pulses from remoter parts of the zone of origin ceased to be overpowered by those from the nearest parts. The motion in that closing phase of the violent part of the earthquake has been compared by an observer to the motion of a vessel in a choppy sea; and I conceive that this comparison is the expression of a veritable analogy.

DISTRIBUTION OF INTENSITY.

When the isoseismal curves for this earthquake are drawn those for the higher intensities will show a remarkable elongation in the northwest-southeast direction. They will also show irregularties expressive of high intensity in the Santa Rosa Valley and other outlying areas. These features are related to the position and form of the zone or zones of origin. If drawn in detail they will show also the great influence of peculiarities of geologic formations. Detailed surveying has been attempted by the State commission only in San Francisco, partly because the results will there have the greatest practical value, and partly because the data are there most available. Notwithstanding the abundance of cracks, landslides, and broken trees in the region of high intensity, it is nevertheless true that natural structures in general are much less sensitive to earthquake violence than artificial structures, and for that reason grades of intensity are most easily mapped in cities.

The word "intensity" has various meanings as applied to earthquakes. As technically defined, it is the acceleration of the earth particle and is a quantity to be measured by the seismograph. But the field of instrumental observation is so limited that another definition practically obtains—that of power to destroy, a property which depends on the duration and direction of the motion as well as its acceleration, and which may have other factors.

It has long been known that buildings and other structures on ground of certain kinds are more susceptible to earthquake injury than on ground of other kinds, and these differences were strikingly illustrated in San Francisco. The general fact appears to be that the amplitude of vibration and the acceleration are greater in loose, unconsolidated formations than in solid rock. The firmer and more elastic a rock formation, the less the intensity of the earthquake shocks it transmits to buildings standing on it; and there is a gradation in this quality from the firmest bed rock to the loosest gravel, sand, and mud. For strong shocks, at least, the intensity is greater in loose formations saturated with water than in those that are dry.

Closely related to the control of intensity by the peculiarities of formations is the subject of surface undulations. Observers of strong earthquakes sometimes report visible progressive undulations of the ground, similar to water waves, and such observations are usually

made where the formations are alluvial. Doubtless many of the observations are fallacious, depending on a subjective illusion as to the direction of verticality, which arises from the horizontal movements of the observer's support; but some of them may also be objective. Not only is there a gradation in physical condition from dry earth through mud to water, but the shaking of a loose formation, whether wet or dry, overcomes the adhesion of particles and thereby imparts for the time being a mobility analogous to that of liquids. It is therefore conceivable that gravity waves, altogether analogous to those of water, may be produced by a violent earthquake on the surface of a loose formation. Certain ridges on soft ground caused by earthquakes in Japan are inferred by Omori and Kikuchi to represent such soil waves and to indicate a wave length (crest to crest) of 20 to 40 meters. The San Francisco earthquake produced a similar ridging on tidal mud in Tomales Bay, the average ridge interval being not more than half that of the Japanese examples. The Tomales Bay ridges are roughly parallel to the fault trace (which is close at hand), have about the same irregularity as wind waves, and originally ranged in height from 1 to 3 feet. They were observed chiefly, but not exclusively, on the body of mud already mentioned as having been shifted toward the southwest shore. The tract shown in Pl. VII lies so low as to be submerged much of the time, and the ridges had been so nearly obliterated when the views were taken that little remained besides an obscure indication of their ground plan; but an area nearer the head of the bay, and probably lying somewhat higher, not only seemed to have preserved its character when photographed (April 28; see Pl. VIII, *A*), but showed little change when visited nine months later.

Notwithstanding the persistence of the ridges at the last-mentioned locality, there is no reason to question the statement that the whole mud plain had the smooth surface common to tidal flats until it was disturbed by the earthquake. Nor do I find any room for doubt either that the ridges originated as waves on the surface of the mud while it was rendered quasi liquid by violent agitation, or that they persisted because the mud promptly resumed its normal coherence when the agitation ceased. It is by no means equally clear that the arrested waves were true gravity waves rolling across the mud plain. Whatever their mechanism and history, they illustrate a mode of response of wet, unconsolidated material to powerful earth tremors, they suggest an explanation of certain wavelike ridges produced on areas of made ground in San Francisco, and they contribute to an understanding of the peculiar destructiveness of the earthquake in such areas.

THE EFFECTS OF THE EARTHQUAKE AND FIRE ON VARIOUS STRUCTURES AND STRUCTURAL MATERIALS.

By Richard L. Humphrey.

GENERAL DISCUSSION OF THE EARTHQUAKE CONDITIONS.

On the 18th of April, 1906, the whole civilized world stood aghast at the appalling destruction which visited the city of San Francisco and vicinity. Three weeks later, for the purpose of studying the effect of the earthquake and fire on structural materials, the writer began the investigation herein described, lasting six weeks and covering the entire affected territory. It would be impossible, however, to describe the extent of the damage adequately or comprehensively in a report of this character. When we consider the terrific destruction wrought in the surface of the earth by the first movement or "slip," which developed structural weaknesses, it is not surprising that this movement and the resulting vibrations should prove so fatal to the structures of man.

In the fire that followed hundreds of thousands of people were rendered homeless and dependent on public bounty for shelter and the necessities of life. This phase of the disaster appealed to popular sympathy and drew spontaneously from all parts of the country contributions of food, clothing, household furnishings, and money for the relief of the destitute.

To the user of the materials of building construction the study of the behavior and relative efficiency of the various classes of such materials under the unusual and rigorous conditions imposed by the earthquake and fire is most interesting and instructive. The test was one of such violence that only structures of first-class design and materials and honest workmanship could survive. Flimsy and loosely built structures collapsed like houses of cards under the terrific wrenching and shaking, and many of the structures which withstood the earthquake were subjected to a second test in a fire which surpassed all the great conflagrations of recent years. Some of these structures

which successfully withstood the first test failed signally under the second, by reason of inadequate fireproofing. A very few withstood both tests successfully.

It is a generally accepted fact that no structure could have withstood the stresses produced by the movement of the earth at the "fault trace," along which the maximum intensity of disturbance was localized. The stresses produced by the vibrations at other points, however, could have been resisted with safety if proper design, first-class materials, and honest workmanship—constituting the whole secret of earthquake-resisting power—had been employed in the structures so located. In tall structures rigidity of construction, attained by adequate diagonal and portal bracing, is absolutely essential. In such buildings, owing to the inertia of the mass of the upper portion, the maximum bending moment exerted by the earthquake was applied at some point between the foundation and the top—generally just below the middle. While reenforced-concrete structures were few in the zone of seismic disturbances, these few stood the test by earthquake and fire in a highly satisfactory manner. Rigidity and stiffness and a high fire resistance are inherent qualities of concrete, and this material proved admirably suited to resist these extraordinary tests.

The destruction was greatest in structures built on filled ground, or on alluvial soils in the valleys of rivers, with foundations which did not go through to solid ground, the settling of the earth caused by the vibrations resulting in permanent displacement or distortion of such structures. At many places where great destruction took place, as at Palo Alto, San Jose, Salinas, Santa Rosa, etc., the structures were built on soft ground. In structures built on solid ground or rock formation the action was much less severe and was confined to shaking, producing a maximum oscillation in the upper portions of the structure.

In order to understand properly the conditions under which such destruction as that caused by the earthquake could occur, one should study the geologic conditions prevalent just prior to the earthquake.

The history of the Pacific coast is replete with records of seismic disturbances, the entire region being in a condition of unstable equilibrium and cut by long rifts in the surface, called "faults," which have produced a series of long, narrow valleys. The forces which produce elevations and subsidence of the surface also produce stresses, which finally overcome the adhesion of the opposing rift walls, and earthquakes take place in the slipping of these walls, through a few inches or a few feet, in the effort to adjust the stresses. These earthquakes are of two classes—volcanic and tectonic. The former occur in regions of volcanic activity, are shallow in extent,

and affect comparatively small areas; the latter not only extend to a much greater depth, but also affect much greater areas. The region north and south of San Francisco is regarded as particularly susceptible to earthquakes of the latter type.

A. C. Lawson has traced several of the "faults" referred to, and about ten years prior to the San Francisco earthquake he indicated the location of the present fault trace south of the Golden Gate. His relief map of California serves to show the lines of known faults by the parallelism of the ridges and valleys. In following these valleys one finds evidence of faulting on every hand—the scars and markings on the earth and rocks, and the presence of little lakes or ponds without visible source of supply other than the watershed of the adjacent ridges. According to Lawson, the coast of California is rising, and the seismic disturbances whose record is found in the rocks have been produced by movements in the process of upheaval and subsidence, of folding and faulting, which are, perhaps, greater along the coast of California than in any other part of the world. Whatever may be the causes of these movements, it is apparent that the resultant stresses relieve themselves by producing these faults or rifts in the earth's surface.

The average Californian becomes accustomed to the earthquakes which produce "temblors" of sufficient intensity to rattle windows. Prior to the great earthquake of April 18, 1906, these temblors were of frequent occurrence, but occasioned no alarm and, indeed, scarcely excited a passing interest. Over two hundred earthquakes were recorded during the period from 1850 to 1886, being more prevalent in the vicinity of San Francisco Bay than elsewhere. The writer is informed that during the period just prior to April 18 few if any noticeable temblors occurred. It is fair to assume, therefore, that the great earthquake resulted from an accumulation of stresses which would ordinarily have been relieved by smaller movements.

The relative intensities of earthquakes are indicated, on the Rossi-Forel scale, by Nos. I to X. All under V produce no visible destruction, and from V the destruction increases up to X, which represents those in which complete destruction takes place. The writer understands that the earthquake of April 18 is rated at IX on this scale.

This earthquake, the most severe in the history of the State, took place at 5 hours 13 minutes and 38 seconds a. m., Pacific time, the main shock lasting one minute and five seconds. Between this time and 7 a. m. about thirty minor shocks were recorded. A zone of destruction 50 miles wide was produced, extending for a distance of 150 to 200 miles north and south of San Francisco (see the map, fig. 1, p. 3), beginning at Point Arena, paralleling the coast to Fort Ross,

passing under the ocean bed just west of the Golden Gate, reappearing on the land at Mussel Rock, and following the Pilarcitos and San Andreas pipe lines of the Spring Valley Water Company in a direct line to Hollister. The zone included San Francisco Bay, Russian River, and the Sonora, Santa Clara, and Salinas valleys. The first movement was along this zone in a southeasterly direction, and the vibrations set up on all sides produced a continuous twisting, rocking, wrenching movement that brought down chimneys, walls, towers, etc. In the opinion of the California earthquake investigation commission the slip commenced at the northwest end of the zone, and the force which occasioned the rupturing or shearing movement was a progressively decreasing one to the southeast end. As in the earthquake of 1868, the destruction was greatest in proportion to the nearness to the fault trace, and in parts built on soft or alluvial soil, or on "made ground." The earthquake as recorded by the seismographs showed a horizontal movement of about 3 inches and a vertical movement of about 1 inch, the velocity of propagation being about 2.1 miles per second. The wave movement was long and slow in hard soil and rock and comparatively short and incoherent in soft ground.

EFFECTS ON STRUCTURES OUTSIDE OF SAN FRANCISCO.

In considering in detail the damage wrought by the earthquake one must look for evidence in the country surrounding San Francisco, since the fire in that city obliterated most of the signs of the damage.

The greatest loss in the city of San Francisco was principally the result of the fire, which was rendered uncontrollable owing to the wrecking of the water-supply system by the earthquake. (See the maps of the city and vicinity, Pls. LVI and LVII.) An examination of the damage to the system at once suggests itself, especially as some of the main conduits are located on or near the fault line.

The city is supplied principally by gravity from three main distributing reservoirs, viz, University Mound, College Hill, and Lake Honda; there are also two supplementary sources—Alameda Creek, on the east side of the bay, and Lake Merced. The University Mound reservoir, having a capacity of 33,000,000 gallons, is supplied from Crystal Springs Lake through 17 miles of 44-inch wrought-iron pipe, carried for a considerable distance on trestles over the marshes. The College Hill reservoir has a capacity of 15,000,000 gallons and is supplied from San Andreas Lake through 14 miles of 44-inch, 37-inch, and 30-inch wrought-iron pipe. The Lake Honda reservoir, with a capacity of 31,000,000 gallons, is fed from Pilarcitos Lake through 16 miles of conduit, 1½ miles of which is wooden flume and the remainder cast-iron and wrought-iron pipe and brick tunnel. Of the two supplementary supplies, the water from Alameda Creek is car-

ried 27 miles, crossing San Francisco Bay through submarine pipes, and thence passing through the Crystal Springs conduit to the city; that from Lake Merced is pumped into the Pilarcitos conduit and thence to the city.

In company with Herman Schussler, chief engineer of the Spring Valley Water Company, the writer made a detailed examination of the principal conduits and reservoirs. On the San Bruno marsh the 44-inch line to the University Mound reservoir had been thrown off the trestle for a distance of 1,300 feet; and, while the pipe was readily repaired, the trestle had to be rebuilt, as many of the timbers had rotted. Near Baden the line had been telescoped 42 inches, shearing off an 8-inch gate valve. The reservoir itself was undamaged, yet its three days' supply was rendered useless by the breaks in the cast-iron distributing mains.

The only damage done to the conduit between San Andreas Lake and the College Hill reservoir was at Baden, where the slip joint had been broken, tearing out the four cast-iron lugs—an effect indicating a force of at least 2,000,000 pounds.

The principal breaks in the Pilarcitos conduit, which was so badly damaged that the company decided to abandon it, were examined. This conduit had been located for convenience in one of the long, narrow valleys, and therefore on the line of an old fault. It is evident that it would be futile to attempt to build this conduit strong enough to withstand a slip on the fault line. The breaks in this 30-inch wrought-iron pipe ranged from 30 inches to 6 feet in length. At other points it was telescoped and twisted beyond repair. (See Pl. IX.) The Pilarcitos conduit crosses Frawleys Gulch on a trestle. The movement of the earth produced a compression in the pipe line at this point, which threw it off and wrecked the trestle, and the water in the conduit leading to the trestle line was released so rapidly that it formed a vacuum, which caused this conduit to collapse, as shown in Pl. X, A. The conduit crosses and recrosses the fault for a distance of 6 miles south of Frawleys Gulch. The 30-inch wrought-iron pipe line was torn and twisted at each crossing, while the earth dam of Pilarcitos Lake was uninjured.

The San Andreas earth dam lies across the fault, the crossing being about 100 feet from its east end, and the dam shows a disturbance for a distance of more than 100 feet. One of the worst cracks runs diagonally across a culvert 4 feet 6 inches in diameter, which appears to be uninjured. Although San Andreas Lake had considerable water in it, no appreciable loss of head was observed. There is a roadway over the dam, along which runs a fence. Both were offset at the fault line about 3½ feet. A wooden flume used for diverting storage water to the reservoir lines crosses the fault, and was wrecked at that

point for 50 feet. A brick conduit used for waste purposes extends across the fault. All the four rings, of hard-burned brick, are laid in first-class Portland-cement mortar, making a first-class piece of work in every way. This conduit, which is 9 feet 6 inches in diameter, was crushed together at the crossing.

The Searsville dam, a structure similar to the San Andreas earth dam, 1 mile east of the fault line and parallel to it, was also found to be uninjured.

Very little damage was done to the pumping stations, and the steel standpipes of this company were not injured. The Lake Honda reservoir was slightly damaged by a crack in its concrete lining. No damage was done to the Alameda Creek supply, except to the connection at the Belmont pumping station.

The concrete dam near San Mateo, at the lower end of Crystal Springs Lake, parallel to the fault line and a few hundred feet east of it, was undamaged. This dam, a view of which is given in Pl. XI, *B*, is built of large blocks of concrete, thoroughly keyed together and molded in place, each block containing between 200 and 300 cubic feet. The dam is 680 feet long, with a present height of 146 feet. When completed it will be 170 feet high, 176 feet thick at the base, and 25 feet thick at the top. It is arched upstream to a radius of 637 feet.

The clay-core earth dam of the upper Crystal Springs Lake lies across the fault line at nearly right angles. This dam is now maintained as a county causeway, equalizing pipes having been placed through it. At the time of the earthquake the water was at the same height on each side, and the absence of any "head" made it impossible to tell the extent of the damage. The dam moved about 6 feet, however, this fact being shown clearly by an offset of that amount in the fence which runs across it. The roadway over the dam also shows the same offset, although not so clearly.

The water supply of San Francisco, as compared with that of other cities, was fairly good and had a rated capacity of 36,000,000 gallons per day. The failure to control the fire by reason of the crippling of the water supply was not due to the failure of the system outside of the city, but to the breaks in the distributing mains within the city, which rendered unavailable about 80,000,000 gallons of water stored within the city limits. These breaks occurred (see the map, Pl. LVI) wherever the pipes passed through soft or made ground. No breaks occurred where the cast-iron pipe was laid in solid ground or rock. It is evident that in earthquake countries water-supply pipes, at least, should be so laid as to avoid the action of slips, settling, and ground movements of all kinds. The pipe lines should also be arranged with gates and by-passes, making it possible to cut

out any portion of the system which may become crippled. There should also be some means of preventing the loss of water which is occasioned by breaks in the house service pipes.

While one of the main conduits was badly damaged wherever it crossed the fault, this damage was no greater than that done to any other structure that was situated at the fault line. Structures so located were torn apart, the gap in the case of a fence (Pl. I, *B*) or road (Pl. I, *A*) being from 6 to 20 feet, according to local conditions. In the country around Fort Ross there were many trees located on the fault that showed the effect of the slip. Great redwood and pine trees were either twisted out of normal position or split (Pl. II) from the roots up for distances of 35 feet or more, even when perfectly sound. This splitting action was due to the earth on the west of the line of faulting moving the roots on that side, a motion which tended to pull the tree apart. Where the tree had some defect or was unsound (as from dry rot) the action was even more marked and the destruction much greater. Redwood trees grow to great heights and are perfectly straight, and to find one out of plumb is very unusual.

Another interesting example of the effect of the slip along the line of the fault is afforded by the Southern Pacific Railroad bridge over Pajaro River near Chittenden station. This bridge crosses the fault obliquely at a very acute angle—about 10°. It consists of two girder shore spans of 50 feet each and three Pratt truss river spans of about 100 feet each. The piers and abutments are built of concrete, with granite coping and bridge seats (Pl. XI, *A*). The bridge was badly racked by the movement of the earth, which dragged the piers and abutments. The movement of the south abutment was about 24 inches, a distance sufficient to leave the girder without support. The ground also moved a greater distance than the abutment—perhaps 8 or 10 inches farther. The movement of the earth tending to pull the piers from under the trusses was resisted by the anchor bolts, resulting in a cracking of the piers, apparently on the lines marking the different daily batches of concrete used in constructing them. The granite caps were moved out of position and many of them cracked, and the anchor bolts were twisted and bent. The bridge was put into service by the construction of a timber support.

In the vicinity of Los Gatos, where the line of faulting passes through the Santa Cruz Mountains, it crosses the first tunnel of the narrow-gage railroad to Santa Cruz near Wrights. In this tunnel a portion of the loose roof, of shale on a layer of serpentine or soapstone, caved in, completely closing the tunnel. A house on this fault line near Wrights was split in twain, the movement of the earth throwing the west side of the house from its foundation (Pl. X, *B*).

The Saratoga reservoir of the San Jose Water Company lies in a saddle of the Santa Cruz Mountains between Saratoga and Los Gatos, and the fault line crosses it at right angles, the cracks extending through the body of the dam. The reservoir was full at the time, but there was no apparent loss of head.

As already stated, in the country bordering the line of faulting the damage done was greater in soft or alluvial soil or made ground. Most wooden water tanks on low supports were wrecked, not only in the vicinity of the fault line but throughout the affected zone, the failure being due to a lack of lateral bracing of the trestle support. Chimneys generally collapsed, the cause being the unequal movement of the inelastic brickwork and the usually elastic frame structure surrounding it. Wooden buildings on good foundations stood well, the chief damage being to the chimneys and plastering. The alluvial or soft soil forming the banks of rivers generally moved toward the river under the earthquake vibrations, the settling of the ground being most marked (Pl. VIII, *B*). The country in the vicinity of Salinas River presented interesting features of this character. The county road crosses the river near Salinas on a wooden bridge, and the slipping of the banks carried the south abutment 6 feet toward the river. The ground was badly cracked and there were a number of slips in the neighborhood. The road leading to Spreckels's sugar mill, 4 miles south of Salinas, was also greatly damaged by the slips. Spreckels's sugar mill (Pl. XII, *A*) is located on soft alluvium. The main building, which is 500 feet long, is said to be the largest sugar mill in the world. The vibrations of the earth jarred the brickwork loose at the end of the building, which buckled in the middle, where there were no floors above the second floor. The damage to other buildings was also extensive. The town of Salinas itself was severely shaken. The high-school building and some of the buildings on the main street were damaged, chimneys were thrown down, and a water tank of the Southern Pacific Railroad, supported on a steel trestle near the station, collapsed.

Along the Bay of Monterey the whole shore slipped about 12 feet into the bay, the movement buckling the rails on a railroad trestle and the cars dropping about 5 feet. A frame house and surroundings moved 12 feet, still maintaining their relative positions. In Monterey the principal damage was in the loss of chimneys and cracking of plaster.

At San Jose, located on the soft alluvium of the Santa Clara Valley, the destruction was extensive. The post-office, a very substantial building, lost its tower, which was laid up in lime mortar, and was deficient in lateral bracing. The walls were of brick with a 4-inch or 6-inch stone veneer, and there was a wooden-framed slate-covered apex. The collapse of the tower damaged the pavement, and

to some extent the building itself. The damage to the hall of records, along the end walls, was due entirely to defective construction. The Hall of Justice (Pl. XII, *B*), which was completed in 1905, had the wall along the cornice line thrown down. The reenforced-concrete roof contributed no little to the support of the walls of the building, and had the stonework been less heavy and of better quality the damage probably would not have been so extensive. The high school (Pl. XIII, *B*), a flimsy structure of brick with wooden frame, was so badly wrecked that it had to be torn down as a matter of safety. The destruction of the buildings along First street, the principal business thoroughfare, was also extensive. Lime mortar, flimsy framing, poor design, and lack of tie between floor and roof members and walls were the causes of these failures.

Perhaps the worst example of poor design, bad workmanship, and poor materials in the earthquake territory, except in the city of San Francisco, is the insane asylum at Agnew, about 6 miles northwest of San Jose, consisting of a main building surrounded by a number of others—all flimsily constructed brick structures with timber frames. The construction of these buildings, with their thin walls (in many places devoid of mortar) and light, insufficient wooden framing, indicates a criminal negligence that is appalling. One hundred and seventeen patients and attendants lost their lives, principally from the fall of the central tower of the main building. The brick stack of the power plant and the towers of surrounding buildings collapsed. In the farmyard near by is a water tank supported on a wooden trestle. This tank moved about 10 inches, while less than a stone's throw away are four water tanks supported by a diagonally braced steel trestle, which were undamaged (Pl. XIII, *A*).

The most interesting ruins are those of the Leland Stanford Junior University, at Palo Alto, 6 miles east of the fault line. These buildings were on a soft soil and were therefore subjected to the severest earthquake conditions; and as they represent several different types of construction they afford a profitable study in the earthquake-resisting power of various structures and structural materials. The destruction was very great, most of the buildings being wholly or partially destroyed.

Three types of wall construction were represented—(1) solid stone, (2) brick and stone veneer, and (3) reenforced concrete. The buildings of the first-mentioned type, which were erected by Senator Stanford by day labor, were examples of good substantial work, and the damage to them was not so great. The stone-veneer buildings represent a later type, resorted to as a matter of cheapness, and suffered the most. The third type, of reenforced concrete, sustained practically no damage. The stone-veneer buildings have a 4-inch or

6-inch face of stone, poorly bedded, containing a large percentage of spalls, the lime mortar being of good quality. The construction is fairly common in other parts of the country. The roof trusses were not anchored to the walls, but to a great extent were butted against the walls; the floor joists rested in the walls and were not tied. Under the vibrations the walls were pushed out of plumb and, having no proper connection with the floor and roof members, collapsed.

The gymnasium and library presented interesting features. The dome of the library was supported by a skeleton of steel, and although the surrounding walls collapsed, this dome was not damaged (Pl. XV, *A*). The gymnasium dome rested on intermediate brick walls, which collapsed with the dome (Pl. XV, *B*).

The boys' dormitory (Encina Hall) was built of stone, and was one of the buildings erected by Senator Stanford. The chimneys of this structure collapsed and crashed through the roof and floors, killing one student and injuring several others. The walls themselves were but slightly cracked. The girls' dormitory (Roble Hall) had walls of reenforced concrete with wooden floors. The chimneys on this structure also collapsed, but no other damage was done, the walls being left intact, without any cracks.

The memorial arch (Pl. XVI) was a poorly designed structure, 100 feet high, with stone-veneered walls. The structure above the arch ring was hollow, and an attempt had been made to stiffen it by the use of a number of I beams. These beams were not tied to the stonework, but simply rested upon it, and under the action of the earthquake they became battering rams and helped to accomplish the destruction of the arch. The arch as first designed was 75 feet high, and it will be noted that the earthquake reduced it to the height originally intended (Pl. XVI, *B*).

The memorial chapel, one of the most beautiful buildings in this country, was almost completely wrecked (Pl. XVII, *B*) by the collapse of the tower. A platform of steel beams had been placed under the clock as a precaution against the chance falling of the pendulum, and this platform saved the clock. The damage done to the mosaic work and the interior decoration is probably irreparable.

The chemical laboratory was damaged by falling chimneys, and gable walls were pushed out and suffered considerable damage by the collapse of the assay stack. The plastering was also badly cracked. Great damage was also wrought in the power plant of the mechanical engineering department by the falling of the stack.

The quadrangle, or main academic portion of the university, was built by day labor and was a fair piece of work. The cloister (Pl. XVIII, *B*) suffered considerably, the bases and caps of the columns being spalled and chipped, indicating that they must have been subjected to a rocking motion. The arches apparently opened up, for in

a number of them the arch stones had dropped partly out of place. The department of geology (Pl. XVIII, *A*), the newly completed end of the quadrangle, suffered the greatest damage; many of the walls will have to be rebuilt, having been either cracked very badly or destroyed entirely. The plastering was badly cracked and showed the outline of each sheet of metal lath. Where reenforced concrete was used the ceilings were free from cracks.

The most interesting building is the museum (Pl. XIV, *A*), which consists of a central pavilion of reenforced concrete and wings of brick plastered with cement mortar. The columns of the central pavilion are solid concrete, having been cast in place. This building had wooden floors. The wings were wrecked by the earthquake, but the central pavilion escaped injury, although its contents were more or less damaged, principally by being shaken from their positions.

Although the destruction at Stanford University was very great, the character of construction was fair and did not suffer by comparison with that used in other parts of the country. The excellent qualities of reenforced concrete and its ability to withstand earthquake shock were strongly demonstrated.

The town of Palo Alto suffered considerably from the earthquake. Chimneys were generally thrown down. A number of buildings were wholly or partly wrecked, the causes of the failures being similar to those in other sections, consisting largely of defects in design, lack of adequate bracing, poor mortar, and bad workmanship. Three concrete-block buildings were either wholly or partly destroyed and have especial interest, since they have been cited as evidence of the failure of concrete blocks. Two of these buildings are located on Alma street opposite the station and on opposite sides of University avenue—the Thiele Building (Pl. XVII, *A*), a partially completed three-story structure, which was entirely wrecked, and the Fuller Building, a two-story structure, which also collapsed. The concrete-block walls, 13 inches thick, laid in cement mortar, were not braced in any way—the joists, 1½ by 13, simply resting upon the wall. When the building vibrated, the wall was pushed out and collapsed because there was nothing to restore it to its normal position. This defect was more clearly shown in the one-story building of Vandervoort Brothers (Pl. XIX, *B*), in which the roof truss was simply butted against the block wall without tie or other connection.

At Santa Rosa the destruction was greater than in any other section affected by the earthquake, and the fire that followed completely wiped out the business section of the town, which suffered a greater proportionate total loss than San Francisco. A concrete-block building (Pl. XIX, *A*) in this town escaped with slight damage at the cornice only, where the blocks were thrown down, the reason being that the walls were tied to the roof timbers by tie-rods which

held the walls and roof together and made them move as a unit. The cornice was rebuilt before the view was taken. While buildings of brick and stone collapsed all around this one, it received practically no damage and demonstrated that structures that will successfully withstand earthquake shock can be built of concrete blocks. The other buildings at Santa Rosa did not present any interesting features, as they were mostly defective in design and workmanship and the material was generally poor. The city hall, the court-house (Pl. XIV, *B*), the Masonic Temple, the Keegan-Brush Building, and the St. Rose Hotel were all completely wrecked, and added their testimony against poor mortar in brickwork, light wooden frames, and insufficient bracing.

Towns like Berkeley and Oakland did not suffer as greatly from the earthquake as many neighboring towns, the reason lying in the fact that these towns are built on solid ground or on rock. In Berkeley, while chimneys were shaken down, there was no extensive earthquake damage. The Greek Theater, a massive structure of concrete, was uninjured. In Oakland, however, greater destruction occurred. Just outside of Oakland is located the Mills College for Girls. The science building had brick walls plastered with cement mortar, and was considerably damaged by the shaking it received and the falling chimneys. The building had wooden floors and was considerably racked, the walls being pushed out slightly. Within a few feet is the bell tower (Pl. XX, *B*), a reenforced-concrete structure 80 feet high with walls 4 inches thick, which was not damaged in the slightest degree.

CONDITIONS IN SAN FRANCISCO.

GENERAL EARTHQUAKE CONDITIONS AND EFFECTS.

Within the city of San Francisco (see the map, Pl. LVI) the havoc wrought by the earthquake depended on the character of the construction and its foundation. Bordering San Francisco Bay, from Telegraph Hill to Mission Creek, the land consists of mud flats, which have been gradually filled in, and on this land many large commercial buildings had been erected, among others being the Union Ferry building, the post-office, the mint, and the custom-house. Adjoining this filled land was comparatively level ground composed of sand and clay formed by the wearing away of the hillsides and by the incoming sand from the seacoast—a fringe of soil on which were located many of the principal buildings. From Telegraph Hill southwestward along Russian Hill to Sutro Heights runs a ridge of rocky hills composed of indurated clay shale, with serpentine and other rocky formations on their highest summits.

The signs of destruction wrought by the earthquake in the city of San Francisco were more or less obscured or in many places entirely obliterated by the fire. The best evidence of the earthquake can therefore be obtained outside the burned district, and the following notes cover the most important examples of damage due to the earthquake alone.

As in districts outside of San Francisco, the greatest damage was done to those structures having insufficient foundations built on soft alluvium or filled ground. The settling of the ground in the mud flats along San Francisco Bay and of the filled ground in old water courses was accompanied with great destruction. It was in such ground that the greatest number of breaks occurred in the cast-iron gas and water mains and the sewers. The breaks in the sewers were not so evident as those in the gas and water mains, for the reason that the latter were under pressure and breaks in them resulted in breaks in the streets themselves. The most noticeable destruction resulting from the settling of soft or filled ground occurred in Howard and Shotwell streets between Seventeenth and Eighteenth streets, Bryant street betwen Ninth and Tenth streets, Dore street between Bryant and Brannan streets (Pl. VI, *A*), and at the corner of Seventh and Mission streets. The settling was greatest in Howard, Dore, and Bryant streets, being in Dore street at least 5 feet.

On solid ground the earthquake had a rocking effect which produced X cracks (Pl. XXII, *A*) in the brick or stone walls of those buildings which were deficient in diagonal bracing. This was especially true in the upper stories of tall buildings, the cracks generally appearing in the piers between windows or around doorways. The brick curtain walls of buildings well braced diagonally, brick walls reenforced with band iron, and well-buttressed brick walls, as in such old structures as the Palace Hotel, Sailors' Home, St. Mary's Hospital, Synagogue Emanuel (Pl. XXI, *B*), and others, and walls of reenforced concrete proved best adapted to withstand this rocking action. The Palace Hotel was stiffened with cross walls in addition to the band-iron reenforcement in the brickwork, and is in good condition as far as earthquake effects are concerned. It was completely gutted by fire, however (Pls. XXX, *B*; LII, *B*), being a nonfireproof structure with wooden floors and roof which yielded readily.

Weak and flimsy framing, insufficient bracing, and poor mortar were the cause of most of the failures in San Francisco. The Albert Pike Memorial, a recently completed building on Geary street west of Fillmore, was seriously damaged, and so also was the adjoining Jewish synagogue (Pl. XXI, *A*), which had not been quite completed. Both buildings are examples of defective design and workmanship. In the girls' high school the damage to the brick walls resulted from a lack of proper tie between the floor and roof timbers and the walls

and the poor quality of the mortar used in the brickwork. Again, in the Hahnemann Medical College, on California street near Maple street, the destruction of the end walls was the result of bad design, the roof trusses butting against the walls and the floor timbers resting upon the walls without adequate tie. The poor quality of the mortar permitted a ready disintegration of the brick-veneered walls, although some band iron had been used for the purpose of strengthening them. The Cathedral of St. Dominic, with its high, unbraced brick walls and its peculiar wood-sheathed spires, also proved a victim of poor design and workmanship; the sheathing on the spires was shaken off and the collapse of the walls resulted in extensive damage to the interior.

In interesting contradistinction to these failures was the Sailors' Home, erected in 1858 for use as a marine hospital and condemned as unsafe after the earthquake of 1868. Its heavy brick walls, reenforced with band iron and further stiffened by cross walls thoroughly bonded, are in excellent condition. The building rests upon rock and the framing is excellent; the rafters are fastened to a wall plate which ties the walls, causing the structure to move as a unit. The only cracks occurred where partition walls which had been added were shaken loose from the main walls and around the archways leading to the main stairway on the second and third floors, where no extra stiffening of the walls had been provided. The building in all other respects suffered no damage, there being no new cracks apparent in the exterior walls.

The old red-tiled Spanish Mission Dolores (Pl. XXIII, *B*), built in 1777, with its adobe walls and wooden frame, was not injured, while its more modern successor was greatly damaged. The complete collapse of the tower of the new Mission Dolores was not brought about directly by the earthquake, but the damage was such that the tower had to be taken down, as shown in Pl. XXIII, *B*.

The group of buildings comprising the plant of the San Francisco Gas and Electric Light Company, built on the soft ground along San Francisco Bay just west of Fort Mason, was badly shaken, and none of the buildings escaped damage. The collapse of the stack wrecked the light slate-covered iron roof of the power house and started the fire that destroyed the roof of the boiler house. The ground settled very considerably under the vibrations of the earthquake, and further destruction was caused by the unequal settling of the building. The main shock appeared to come from the north, and the north walls received the greatest damage. The end wall of the retort house was pushed out 1 foot at the center, but was saved from collapse by the tie-rods which held it to the roof truss. The walls were cracked at the northwest and northeast corners. The scrubber and gas-tar holder houses were wrecked, the heavy wooden

roof trusses collapsing. Nearly every wall was moved slightly, but the brickwork was generally very good, and apparently had cement in it. The exhaust house had three intermediate walls, 18 inches thick at the top. The north wall and the next one fell into the building, the side walls being pushed out 6 inches. The building had wooden roof trusses and the north truss cracked at the center mortise. The floor settled badly around the condensers. The gas holder collapsed from the sudden release of the gas due to a break in the mains. The trestle pier extending into the bay also collapsed.

Most of the structures built on piles along the bay suffered considerable damage, especially the frame sheds on the wharves. The Union Ferry Building (Pl. XLVI, *A*), the terminus for all the ferries plying on the bay, is built on piles. It was more seriously damaged by the earthquake than would appear at first sight, and barely escaped the fire also. It is of interest to consider in some detail the behavior of this structure under the action of the earthquake. The ten-story tower was so seriously damaged as to require the removal of the masonry walls, and will probably have to be rebuilt. This tower consists of a steel frame which was inclosed with heavy sandstone walls backed with brick for several of the lower stories, and with sheet metal above. The floors above the masonry part were of stone concrete reenforced with expanded metal between I beams. The brick walls were badly shattered, and a large section was thrown out just below the clock on the west front, while on the east front a large mass fell through the skylight onto the upper story of the main building. There were but few cracks in the north and south walls. The steel time-ball staff was badly bent, indicating a considerable movement of the top of the tower, probably resulting from the first shock. The steel work was severely racked, the greatest damage being just below the middle. Some of the diagonal braces were sagged, having been stretched beyond their elastic limit (Pl. XLVI, *B*). In the southeast corner of the third story the bottom and top loops of one of the 2-inch square diagonals were pulled apart, and several of the rivets in the angle connection were sheared off; in the southwest corner also the top diagonal loop pulled apart, the diagonal being considerably bent; in the northwest corner seven of the eight ¾-inch rivets in the angle of the connection for the diagonals were sheared off (Pl. XLVII, *B*); and in the northeast corner all but 2 inches of the top angle was sheared, and the north diagonal was bent, the loop having been pulled apart. On the second floor, in the northeast corner, the top east diagonal connection pulled away, shearing the rivets; in the southeast corner the top angle of the diagonal connection sheared for about 2 inches, and four of the 1-inch rivets holding the cover plate of the southwest column (Pl. XLVII, *A*) were sheared, as were also

two of the rivets holding the clip support for the west girder. The floor of the main building consisted of groined arches of stone concrete springing from concrete piers supported by cluster piles. The self-supporting walls of sandstone backed with brick were more or less shaken, and the piers of the driveways were badly cracked; the floors were of stone concrete reenforced with expanded metal between I beams and supported by cast-iron columns. The concrete in this building appeared to be undamaged.

Most of the entrances to the cemeteries were wholly or partially wrecked, and the burial vaults and gravestones were all more or less disarranged. It has been estimated that perhaps 60 per cent of the monuments, vaults, etc., in cemeteries were overturned or moved.

In Golden Gate Park nearly every stone or brick structure was damaged. The emergency hospital, a single-story brick and stone-veneered building, lost its gable walls and was damaged in the same manner as other structures having improperly bonded walls laid in lime mortar, and deficient in proper ties between the masonry and the other structural parts. The gable walls of the restaurant in the children's playground were thrown down by the earthquake, but the greatest damage resulted in the settling of the foundation of one of the columns, which caused the collapse of the structure. The music stand, a stone-veneer brick-backed structure, was racked and shaken. Part of the pediment was shaken loose, and many of the columns were spalled and moved. Some of the walls of the museum were thrown down, and its contents were more or less damaged. All the monuments were damaged. The Francis Scott Key monument (Pl. XX, *A*) was racked so badly that the arch stones were shaken loose, the columns spalled at cap and base, and the monument as a whole moved on its foundations.

The most interesting structure in Golden Gate Park is the cyclorama (Pl. XXIII, *A*), on the top of Strawberry Hill, built about fifteen years ago. The top of the hill had been leveled off in order to form a foundation. The cyclorama consisted of circular walls of reenforced concrete, the aggregate of which was a hard shale crushed to concrete size. This material was very inferior and yielded a poor concrete. The reddish-brown effect was obtained by means of a veneer ($1\frac{1}{2}$ to 4 inches thick) of a concrete consisting of crushed brick, sand, and cement. The reenforcement in the base consisted of four $\frac{7}{8}$-inch cables of thirty strands each. The reenforcement of the columns consisted of $\frac{3}{4}$-inch twisted bars and $\frac{1}{2}$-inch stirrups. The entrance, with its very heavy, massive top, should have been of hollow-construction reenforced concrete. The settling of the foundation or fill under the vibration of the earthquake caused the structure to collapse. The slip (Pl. XXII, *B*) occurred principally on the northeast side, the movement being 4 or 5 feet. The principal crack in

the base was about 11 inches wide, with a half-inch horizontal crack leading from it along the reenforcement. The floor is in good condition, except the pavement, which broke into blocks, most of the planes of fracture coinciding with the actual joints between the different sections. Under the circumstances—the undermining of the foundation by the slip as described—the structure developed remarkable strength. No brick or stone structure could have stood the shock so well. The rustic railing around the outside of the walk (Pl. XXII, *B*), which was of wrought-iron pipe covered with wire mesh and plastered with Portland-cement mortar, was distorted by the slip, but otherwise uninjured.

At the bottom of Strawberry Hill is a bridge crossing over Stow Lake. This bridge is made of concrete, and showed no signs of cracking, although the banks of the lake slipped into the water.

BEHAVIOR OF INDIVIDUAL STRUCTURES.

GENERAL STATEMENT.

The numerous fires that broke out all over the city were doubtless caused by the collapse of chimneys and the breaking of electric connections. These fires were at first confined to the territory south of Market street, and it is said that by 8 a. m. on the morning of April 18 more than fifty fires were recorded. The early failure of the water mains rendered the city helpless and placed it at the mercy of the flames, the fury of which for three days threatened to complete one of the greatest disasters of recent years and to obliterate one of the most beautiful cities in the country. The conflagration was finally checked, at the barrier presented by a wide avenue, by a change in the direction of the wind and through the efforts of the fire department, using water pumped from the bay at the foot of Van Ness avenue.

San Francisco consisted principally of frame and brick structures, with perhaps forty or more so-called "fireproofs," a few buildings of slow-burning construction, and the substantial Government buildings. Many of the buildings contained mercantile stocks, and most of them were exposed to exterior fire conditions of maximum severity. Since every type of construction was represented, the ruins afford a most excellent opportunity for comparative study, although the scope of the information obtained is incomplete, as a water test is lacking.

In comparing the behavior of the various structures and structural materials it has been thought best to describe the condition in which certain individual buildings were left by the earthquake and fire, and to present the salient features of these buildings by illustrations with descriptive legends. The following descriptions, which for

convenience are arranged in alphabetical order, cover the structures not previously mentioned that were inspected by the writer, the total number embracing nearly every building that was left standing in the burned district. The locations of these buildings can be found by reference to the map, Pl. LVI, and to the panorama, Pl. LV.

ACADEMY OF SCIENCES BUILDING.

The Academy of Sciences building, 819 Market street, views of parts of which are shown in Pls. XXIV, *A*, and XXV, *B*, was of ordinary concrete construction and six stories high, and was completely destroyed.

A six-story annex having brick walls, concrete-filled cast-iron columns, and reenforced-concrete floors, was connected to the main building on the rear. The brick walls of the annex were badly cracked by the earthquake, and the building was subsequently completely gutted by fire. The structure itself passed through a fairly hot fire successfully, although surrounded by buildings which were completely wrecked. Plaster of Paris was used on the concrete-filled cast-iron columns and seemed to stand fire much better than lime mortar. These columns are shown in Pl. XXV, *B*, a view taken from the third floor looking southeast. An interesting feature of the building was the concrete-filled cast-iron column that supported the south wall. Owing to the unequal expansion of the cast iron and the concrete the cast iron failed, bulging from the heat and cracking on cooling, as shown in Pl. XXIV, *A*. The ¾-inch or 1-inch thickness of concrete which covered the reenforcing bars proved insufficient in the basement, where the fire was fairly hot. The heat expanded the bars, thereby ripping off the concrete layer and leaving the rods exposed.

ÆTNA (YOUNG, OR COMMISSARY) BUILDING.

The five-story Ætna Building (Pls. XXIV, *B*; XXV, *A*; XXIX, *B*), on the southwest corner of Spear and Market streets, was occupied by the Sellers Brothers Hardware Company. It was built on piles and had self-supporting walls of gray granite, pressed brick, and terra cotta. The steel columns and girders were fireproofed with expanded metal, plastered. The expanded-metal reenforced-concrete floors rested upon steel girders with intermediate ribs of concrete supported by 5-inch by ½-inch bands of steel without fireproofing which hooked onto the top flanges of the girders.

One panel of the fifth floor, which was rather heavily loaded with tin plate, collapsed because of the expansion of the above-mentioned steel bands from the heat, which was sufficient to volatilize the tin even from the middle sheets of the pile. The fall of the load of tin

plate caused the failure of the third floor, as shown in Pl. XXIX, *B*. The plaster protection of the columns was in fair condition, and the columns were uninjured. The principal damage from earthquake was to the brick walls, the south and west walls showing a number of cracks. The granite trimmings around the doorway and the terra-cotta trimmings of the building were badly spalled by the fire, as shown in Pl. XXIV, *B*. The basement floor, which was of concrete 7 or 8 inches thick, was pushed up under the sidewalk, reducing the headroom at this point from 8 feet to 3½ feet, approximately. This bulging was probably caused by settling (Pl. XXV, *A*), as the foundation piling did not extend under the sidewalk.

APPRAISERS' WAREHOUSE (UNITED STATES CUSTOM-HOUSE).

The four-story custom-house building, on Jackson, Washington, and Battery streets, shown in Pl. XXVIII, *A*, passed through both earthquake and fire without injury, although located on the alluvial flats. All the buildings around it were burned, but the fire did not gain a foothold in this building, and there was, therefore, no fire test. As an example of successful resistance of the earthquake test, however, this building stands as a favorable testimony to first-class materials and workmanship. The walls were of brick, with granite ornamentation, and the roof was slate covered. The partitions and cross walls were all of solid brickwork, and the only damage that they sustained consisted of a few cracks in the archways near the stairways on the upper floors.

ARONSON BUILDING.

The ten-story Aronson Building, on the corner of Third and Mission streets, had a steel skeleton with hollow-tile partitions and fireproofing for the columns. The floors were of concrete reenforced with expanded metal.

Two of the columns on the first floor buckled by reason of the failure of the hollow tile (Pl. XXVII, *B*), the columns being shortened about 10 inches. Columns also buckled in the basement and on the fifth, eighth, and tenth floors. In the basement two columns were fireproofed with concrete, and remain in first-class shape, but near them are two badly buckled columns which were fireproofed with terra cotta. This result is an excellent object lesson on the merits of the two systems of fireproofing. The sandstone was badly spalled by fire, and the walls were badly racked by the earthquake. The cast-iron stairways were very much damaged. The fire in this building was not severe.

BEKINS VAN AND STORAGE COMPANY'S BUILDING.

The building in process of construction by the Bekins Van and Storage Company, at the corner of Thirteenth and Mission streets, was the only example of the pure type of reenforced concrete in the city (Pl. XXVII, *A*). Two of the six floors were erected, the walls being made of brick laid in lime mortar and the floors and columns of reenforced concrete.

The walls were badly cracked by the earthquake, but the reenforced concrete was not injured. Considerable furniture stored in the building was burned, and the heat slightly blistered the under surface of the concrete floor, which was still green at the time of the disaster.

BULLOCK & JONES BUILDING.

The Bullock & Jones Building, on Sutter street west of Montgomery street, is an eight-story steel skeleton with floors of reenforced cinder concrete, hollow-tile partitions and column protection, and bearing walls of ornamental terra cotta and terra-cotta pressed brick. The reenforced-concrete floor arches were haunched between steel girders, but were not continuous over the girders.

The earthquake damaged the outside very considerably. The building is of rather flimsy construction, and it is a wonder that the fire did not wreck it. The terra cotta was badly spalled by the fire, especially around the windows, and the hollow tile failed badly, both in partitions and as column protection. The 3-inch terra-cotta partitions failed generally, and several columns buckled on the third and eighth floors (Pl. XXVI, *A*). The elevator inclosure, which was plastered on expanded metal, failed, as did also the cast-iron stairways. The wood covering of the floors and the wooden nailing strips were burned. The concrete floor is in excellent condition. A few panels collapsed where the steel girders were displaced. The distorted unprotected beams and girders around openings show strikingly the folly of unprotected steel work.

CALIFORNIA CASKET COMPANY'S BUILDING.

The building which was in process of construction on Mission street between Fifth and Sixth streets by the California Casket Company was seven stories in height and had a steel skeleton and floors of reenforced cinder concrete. The self-supporting walls were built on the sides and rear of brick and on the front of brick faced with sandstone, which was spalled by the heat, although there was no stock and little combustible material in the building. The columns

were fireproofed with concrete. The brick protection around many of the columns was jarred loose, and the brick vaults on the first, second, and third floors were badly cracked around the archways of the openings into them, as shown in Pl. XXIX, *A*, a view of a vault in the second story. The stairways were constructed of concrete with steel channel horses and were cracked in a number of places, especially at the landings. Some of the wooden window frames were burned, but the fire was not very severe either in the building or surrounding it, the greatest damage resulting from the earthquake. The partitions inclosing stairways and elevator shafts were of the usual flimsy metal lath and plaster type. The walls were so badly cracked as to require partial rebuilding, especially at the southwest and northwest corners.

CALL (CLAUS SPRECKELS) BUILDING.

The Call Building (fifteen stories besides the dome), corner of Third and Market streets, was one of the best-designed skeleton buildings in San Francisco. It was fairly well braced laterally, and the workmanship was first class. It stood the earthquake shock well because of its excellent foundation, which extended 25 feet below the sidewalk and consisted of a grillage of steel beams embedded in concrete. The main defect was in the fireproofing of the floors and columns, in which terra cotta was used, and the greatest damage to the building was from fire. Although some of the diagonal braces were bent and had apparently been stretched so as to take a permanent set, the general behavior of the structure demonstrates that high buildings subject to earthquake can be erected with safety even on sand foundations.

The floors were of reenforced concrete up to the seventh story and of hollow-tile arches above, topped with cinder concrete. The partitions were principally 3-inch hollow tile, and these failed very generally. The terra-cotta fireproofing around the columns proved ineffective, and although the steel did not buckle, the paint had been burned off the metal. Wood floors laid on wood nailing strips were used in all offices and were all destroyed by fire. The marble tiling and wainscoting of the corridors was either shaken down by the earthquake or destroyed by the fire. The stairways had cast-iron horses and marble treads, most of the latter being calcined. The suspended wire lath and plaster ceilings were generally destroyed because of the lack of proper fastenings. The curtain walls of granite and sandstone were not damaged by the earthquake, but were considerably spalled by the fire.

CHRONICLE BUILDINGS.

The Chronicle buildings, corner of Market and Kearney streets, comprised an old ten-story structure and a new fifteen-story annex that was in process of construction, both shown in Pl. XXX, *B*. The old building consisted of steel beams and protected cast-iron columns, with self-supporting walls, which had a brownstone front up to the second story and were ornamented with terra cotta above. The floor was of hollow tile, filled with cinder concrete and covered with wood. The cast-iron columns were fireproofed with 3-inch hollow tile, and 4-inch hollow tile was used for the partitions. The terra-cotta partitions and fireproofing entirely collapsed. The building appeared to have stood the earthquake shock, and received its principal damage through the fire. The collapse of the western section of the building was probably due to the buckling of the cast-iron columns.

In the annex terra-cotta hollow tile was used for the floor construction, 4-inch hollow tile for the partitions, and 3-inch hollow tile for fireproofing the columns and girders. The curtain walls were built of sandstone, with terra-cotta trimmings for the front walls of the first and second stories, and brick and terra cotta for the remainder. The building was racked considerably by the earthquake, the front walls developing the characteristic X cracks (a number of which may be perceived by a close inspection of Pl. XXX, *B*), due to a lack of diagonal bracing of the steel skeleton. The tiling failed extensively, the lower webs spalling off and the columns buckling in the southwest corner on the upper floors above the roof of the old Chronicle Building. There was little combustible material in the building, and the trim had not started; a few of the wooden window frames only burned; so that the fire test was not great.

CITY HALL AND HALL OF RECORDS.

The city hall (Pl. XXXI) was a brick building, at City Hall avenue, Larkin street, and McAllister street, consisting of steel floor beams and corrugated-iron arches with cinder-concrete filling. It was wrecked by the earthquake and subsequently gutted by the fire. A prominent feature was a central tower, surmounted by a dome built over a structural steel skeleton. Grouped around the dome were a number of cast-iron columns of half-inch metal filled with brick concrete supported on brackets. Some of these columns in falling broke into small pieces. The brickwork was completely shaken from the central tower. The cement-plastered brick walls were laid in lime mortar of generally poor quality and without adequate tie to the steel work. In some places there was an absence

of any mortar, but in others it was very good, the brick walls falling in large masses and the broken bricks showing the mortar to have been the stronger. The massive architectural ornamentations were top-heavy and lacked adequate bracing. The ceiling was formed of corrugated metal against which the mortar plaster was pressed, with intermediate brick partitions where the span of the beams was too great. The expansion of the corrugated-iron arches by the heat produced a rise at the crown, and the softening of the iron caused the arches to fail; they would have been much stronger without the unprotected corrugated iron. In the treasury department a granite column was badly spalled by the fire. The building was a monument of bad design and poor materials and workmanship, and was not, therefore, of such a character that it could be expected to resist successfully the effect of earthquake or fire.

The damage done to the hall of records by the earthquake was not serious, and consisted of the falling of a small section of brickwork from the third story on the west side and other cracks in the walls. The fire, however, destroyed the contents of the building, leaving only the shell standing.

CROCKER BUILDING.

The ten-story Crocker Building, corner of Powell and Market streets, was a steel-skeleton structure, with hollow-tile floor arches, partitions, and fireproofing for columns and girders. The first two stories of the self-supporting walls were granite, and the remainder buff brick with terra cotta.

On the ninth and tenth floors the light Phœnix columns buckled through the failure of the hollow-tile fireproofing. The fire was only moderate, however, and except on the ninth and tenth floors the steel appeared to be in good condition. The weakness of hollow floor tiles for carrying heavy loads was demonstrated in a number of places where the tile floors had been broken by the fall of safes. The lower webs of the floor tiles had failed over extensive areas. The stairways, with their cast-iron horses and slate treads, were not damaged to any great extent. The floors were topped with cinder concrete and covered with wood in the offices and with mosaic in the corridors.

EMPORIUM

In the building known as the "Emporium," 825-855 Market street, west of the Academy of Sciences, the first two stories were fireproofed with terra cotta. Slow-burning wooden construction was used above the second floor. As shown in Pl. XXXII, very little of this structure save the exterior walls was left standing.

FAIRMOUNT HOTEL.

The six-story Fairmount Hotel, California, Mason, Powell, and Sacramento streets, was nearly completed, and the only combustible in it was the lumber used in construction. It consisted of a steel skeleton with floors of cinder concrete reenforced with expanded metal. The walls were self-supporting and were constructed of granite backed with brick up to the third floor and of light-colored terra cotta in the upper stories. The ceilings were of the suspended type plastered on metal lath. The original plans called for the columns to be fireproofed with concrete, but because of the greater expense of this material the plans were changed and the expanded metal and plaster partitions were molded around these columns. The result was that even under the moderate heat to which the building was subjected about 40 of the columns buckled, including 23 on the third floor alone (Pl. XXXIV), and the partitions were completely wrecked. The effect of the earthquake shock was principally confined to the west end of the north front. The terra cotta was spalled considerably and the granite only slightly by fire. The exterior damage was not very great.

JAMES FLOOD BUILDING.

The steel-frame twelve-story James Flood Building, on the northeast corner of Powell and Market streets, was constructed with segmental hollow-tile floor arches topped with cinder concrete and suspended ceilings plastered on metal lath. The columns were constructed of Z bars and were filled with common brick to the outer edge of the section and the whole inclosed with 3-inch hollow tile. This tile failed (Pl. XXXV, *A*), although the fire could not have been very severe, for the wooden floor in the offices was only partly burned and there were a number of wardrobes and switch boxes of wood, besides the door and window frames and wainscoting, which were not burned. The stairways, which had cast-iron horses and marble treads, were in fair condition. The corridors were tiled with marble. The stonework was very slightly spalled by fire, and the principal damage by earthquake was a cracking of the sandstone at several of the entrances (Pl. XXXIII, *B*).

GRANT BUILDING.

The lower floor of the Grant Building, at the southeast corner of Seventh and Market streets, was used for a bank, the upper floors for offices. It was eight stories high and had a steel frame with cinder-concrete floors, the beams and girders being of solid concrete. The first story had self-supporting walls of sandstone, and the remaining

stories walls of pressed terra-cotta brick, trimmed with sandstone. Hollow tile was used to fireproof the columns and for the partitions.

The cast-iron stairways with marble treads were damaged but slightly. The hollow-tile partitions were badly wrecked, most of them being thrown down. The building was injured considerably by dynamiting, which partly disguised the damage caused by the earthquake.

HOTEL HAMILTON.

The twelve-story apartment house known as the Hotel Hamilton, on the north side of Ellis street between Mason and Powell streets, was a steel-skeleton structure with floors of reenforced concrete and girders and beams of solid concrete. Plastered wire lath served as a fireproofing for the columns, and the suspended ceilings were of the same material. This construction may be seen in Pl. XXXVI, *B*. Four-inch hollow tile was used in the partitions.

The marble treads of the cast-iron stairway were to a large extent calcined. A number of the columns buckled on the first, sixth, and seventh floors, the wire lath being entirely insufficient. This buckling caused the floors throughout the building to settle. The damage by earthquake to the curtain walls was slight. The sandstone finish of the first four floors spalled but little from the heat; the terra cotta above, however, was considerably spalled.

HIBERNIA SAVINGS AND LOAN SOCIETY'S BUILDING.

The two-story bank building of the Hibernia Savings and Loan Society, on the northwest corner of McAllister and Jones streets (Pl. XXXVII, *A*), was constructed with two street fronts of granite and rear walls of brick. The gallery and a portion of the second floor were constructed of brick and concrete arches. The ceilings and ornamental work were plastered wire lath. The dome was sheathed with copper. The granite fronts, especially around the doors and windows, were badly spalled by fire; other damage to the structure was confined almost entirely to the roof.

HOBART BUILDING.

The five-story Hobart Building, on the north side of Market street near Post street, had bearing walls of brick faced with granite up to the second story and of brick trimmed with terra cotta for the remaining stories. The framework consisted of cast-iron columns with steel girders and beams; the floors of segmental arches of plain concrete. The cast-iron columns were fireproofed with brick in the basement, and with wire lath and plaster on the first floor. The partitions were of 4-inch hollow tile. The ceilings were plastered wire lath attached to the lower flanges of the beams.

The granite columns were spalled practically to destruction by fire, as shown in Pl. XXXVI, *A*. The fire in one section appeared to be very hot and caused a collapse of one of the floors, which was followed by the failure of the other floors of that section of the building.

JACKSON BREWING COMPANY'S BUILDING.

The plant of the Jackson Brewing Company, on the southeast corner of Eleventh and Folsom streets (Pl. XXXVII, *B*), was in process of construction and was wrecked by the earthquake, the damage by fire being but slight. The brick walls were laid in lime mortar of poor quality. The steel beams and girders were supported by cast-iron columns. Many of the various steel members were bolted together with an insufficient number of bolts, the girders and beams resting upon the walls without any tie; the columns, girders, and beams were not fireproofed, and in the eastern half the concrete floor slabs, 6 inches thick, were without reenforcement. Several persons were killed by the collapse of the tower. That this building should have been wrecked is not surprising, as the design was bad and the material and workmanship were very poor.

HALL OF JUSTICE.

A steel frame and floors of cinder concrete reenforced with expanded metal were used in the Hall of Justice, at the corner of Kearney and Washington streets. The earthquake largely wrecked this building (Pl. XXXIX, *A*). The cupola of light steel angles collapsed from the heat after being racked by the earthquake. The walls were laid in lime mortar, and the floor panels were stiffened, as in the Ætna Building, with 5 by ½ inch steel bands. The floors were wood covered and were burned. The suspended ceilings were of plastered expanded metal lath, the partitions of 3-inch expanded metal, plastered, while the columns had a double layer of plastered expanded metal with a 1½-inch dead air space between. The suspended ceilings failed, as shown in Pl. XXXV, *B*, a view taken on the second floor. One of the central basement columns buckled and collapsed 18 inches, presenting the appearance of having punched a hole in the floor. Two of the six-cell prison cages fell through the floors into the basement. The cast-iron stairways with marble treads are in fair shape.

KAMM BUILDING.

The seven-story L-shaped Kamm Building, on Market street, west of the Call Building and adjacent to it on two sides, had a steel skeleton and self-supporting sandstone walls. The floors were of reenforced stone concrete, covered with wood, with hollow partitions and sus-

pended ceilings of plastered wire lath, the steel columns, beams, and girders being also fireproofed with plastered wire lath.

The rear structure collapsed when a number of columns in the basement buckled under the intense heat produced by the burning wall paper, of which there was a large quantity stored in the basement.

KOHL (HAYWARD) BUILDING.

The Kohl Building, on the northeast corner of California and Montgomery streets, which presented a number of interesting features, is of a modern type of steel-skeleton construction, 11 stories in height. The floors were of concrete, reenforced with expanded metal, and the columns were incased with expanded metal, plastered. The partitions were made of hollow tile, with metal-covered frames, doors, and windows. The suspended ceilings were of plastered expanded metal.

The earthquake did but little damage, breaking a few panes of glass and loosening the marble wainscoting. There were also a few cracks in the stone facing at the southwest corner of the first floor. The first, second, third, fourth, and part of the seventh floors were burned, the remainder of the building being undamaged. The structure was surrounded by a series of rather low buildings, and the fire was not severe either on the outside or inside. The character of the inside trim prevented to a considerable degree the spread of the flames. One defect in the construction was in the use of plate glass instead of wire glass for the doors and windows.

MAJESTIC THEATER.

The Majestic Theater, at the corner of Ninth and Market streets (Pl. XXXIX, *B*), although one of the largest and best of the San Francisco theaters, was particularly bad in design. The roof trusses, of about 80-foot span and perhaps 75 feet above the ground, were carried on 18-inch walls insufficiently reenforced by pilasters.

The common brick bearing walls were completely wrecked by the earthquake. The roof trusses over the stage collapsed. The walls still show extensive earthquake cracks, as will be seen from the illustration. The building was subsequently gutted by fire.

MERCANTILE TRUST COMPANY'S BUILDING.

The three-story Mercantile Trust Company's building, on California street east of the Kohl Building, like most of the low structures, appeared to be immune from the earthquake and fire. The principal damage was caused by the falling walls of adjacent buildings, which smashed in the steel roof with its heavy glass and started a fire in the interior. The granite facing around the windows spalled to a slight extent, but the building was not badly damaged.

MERCHANTS' EXCHANGE BUILDING.

The recently constructed modern office building known as the Merchants' Exchange, on California street between Montgomery and Sansome streets, caught fire from the outside and its contents were destroyed. The edifice was 13 stories in height, with steel skeleton, fireproofed with plastered wire lath and reenforced-concrete floors. The floors of the rooms were of wood; the corridors were floored and wainscoted with marble. The fireproofing of the columns consisted of two layers of quarter-inch wire lath with a dead air space between, except those which were bricked into the outside walls. The suspended ceilings and partitions were likewise of plastered wire lath, and the same material formed the walls of the "fireproof" vaults. The curtain walls were of brick on the sides and rear; on the front the first two stories were of granite, the remainder being pressed terra cotta with terra-cotta trimmings. The heat of the fire was sufficient to calcine a large portion of the wainscoting and the marble treads of the cast-iron stairways. Though not completely destroying it, the fire burned the life out of the plaster, all of which will have to be renewed. The rear walls were cracked by the earthquake. The enameled brickwork of the light well (Pl. XL, *A*) also shows earthquake cracks, and is badly spalled by the fire. The stonework was slightly spalled by the heat. The metal frames between the windows opening into the court were buckled, the cinder-concrete fireproofing being insufficient. The terra-cotta trim in the light well was also badly spalled.

MILLS BUILDING.

The eleven-story Mills Building, at the northeast corner of Bush and Montgomery streets, had a steel skeleton with hollow-tile fireproofing and hollow-tile partitions. The floors were also of hollow tile topped with cinder concrete and covered with wood in the offices; the tiling and wainscoting of the corridors were of marble.

The walls were racked by the earthquake. The hollow tile failed and left the steel skeleton exposed to the fire. Just how seriously it was damaged is problematical; four of the basement columns buckled (Pl. XL, *B*), the lower webs of the floor tiles failed over large areas (Pl. XLV, *B*), and the partitions and the marble treads of the cast-iron stairways were destroyed. In the light well the window casings were distorted by heat because of insufficient fireproofing, and the terra cotta, granite, and exterior trim of the wall were badly spalled. Owing to the failure of the floor tile many safes fell through the several floors. The building should be rebuilt.

UNITED STATES MINT.

The massive three-story Government building occupied by the United States mint, at Fifth and Mission streets (Pl. XXXVIII), which was not damaged to any appreciable extent by the earthquake, was inspected in company with the superintendent, Mr. Leach. One of the interior walls was weakened by a break in the sewer which ran under it, and one of the chimneys was cracked at the top. This structure, which is located at the intersection of two wide streets, is built on soft alluvium, but rests upon a substantial pile foundation. The bearing walls were of solid brick faced with granite, the northwest face of which was badly spalled by fire (Pl. XXXVIII, *B*). The floors consisted of brick arches between steel beams, finished in cement. They were supported by cast-iron columns, which were unprotected except where they were incased by the heavy brick wall partitions. The doors and windows were of wood glazed with plate glass, the windows on the first and second floors being fitted with folding inside iron shutters. The roof and northwest side of the third story caught fire from without, but as an artesian well provided an independent supply of water the fire was prevented from gaining a foothold, and the building was but slightly damaged.

MONADNOCK BUILDING.

The ten-story Monadnock office building, on the south side of Market street between the Palace Hotel and the Call Building, was in process of construction and was damaged by the earthquake and by dynamiting in the vicinity, besides being gutted by fire.

The west wall was not erected, as that section was incomplete, pending the satisfactory purchase of the land. The structure had a steel skeleton frame, reenforced-concrete floors, with a ceiling of plastered expanded metal. The columns were incased with two layers of plastered expanded metal, with a dead air space between them. The partitions were 3 inches thick, plastered on wire lath. The floors were topped with cinder concrete and covered with tile in the corridors and with wood in the offices. The corridors were to have been wainscoted with marble also. The building was not adequately braced diagonally. Large areas of the exterior were damaged and will have to come down. Two unprotected columns in the basement collapsed, settling the floors for 7 inches. The building is to be repaired by jacking up the floors and replacing the buckled columns. What effect this will have on the reenforced-concrete floors is problematical. Certainly their factor of safety is reduced, and in the judgment of the writer the building is materially weakened, for the reason that the buckling of the columns, which resulted in the settling of the floor, cracked the floor beams at their points of connection with the

columns. While the jacking up closes the cracks, it can not restore the original strength of the connection, which although not entirely gone has been reduced to a very small percentage of its former value.

MURPHY BUILDING.

The columns of the five-story Murphy Building, at the corner of Kearney and California streets, were constructed of corner angles latticed and filled with cinder concrete, the whole being incased with plastered metal lath, with a dead air space between. The floors consisted of cinder-concrete arches between channels.

This building was completely gutted by the fire, although the structure itself was left in fair condition. The metal-lath ceilings and partitions stood the test fairly well, though some of the partitions were buckled out of shape. A view of this damage on the third floor is shown in Pl. XLI, *B*. The terra-cotta trimmings and the copper work around the bay windows were badly damaged by fire.

MUTUAL LIFE BUILDING.

The nine-story Mutual Life Building, at the southeast corner of Sansome and California streets, was fireproofed throughout with terra-cotta hollow tile, with hollow-tile partitions. The treads of the cast-iron stairways and the wainscoting and tile of the corridors were of marble. The office floors were constructed of cinder concrete covered with wood.

The damage to this building from the earthquake was very slight. The fire in the building, while not severe, was sufficient to cause the failure of the tile fireproofing of the roof trusses, which collapsed from exposure to heat (Pl. XLII, *A*).

PACIFIC STATES TELEPHONE AND TELEGRAPH COMPANY'S BUILDING.

The recently completed eight-story building of the Pacific States Telephone and Telegraph Company, on Bush street between Grant and Kearney streets (Pl. XLI, *A*), embodied many good and a few bad features of construction. The side and rear walls were of brick, and the front was of terra-cotta pressed brick and terra-cotta trimmings. All the walls were self-supporting. The floors were of reenforced concrete between steel beams, and the ceilings for all floors above the basement were suspended metal lath, plastered.

The walls were cracked somewhat by the earthquake, and the pilasters on the exterior were spalled. The girders and columns supporting the floors were fireproofed with concrete and were in excellent shape after the fire. The window protection was excellent; the front was provided with Kinnear rolling shutters, with plate-glass metal-covered windows, while the side windows had

metal-covered sash and frames, with wire glass, and tin-covered sliding shutters. The earthquake racked the front sufficiently to prevent the shutters from working. The heat produced by the burning insulated wire and other supplies was high and protracted. The reenforced-concrete beams of the roof were weakened by heat and will have to be replaced. The concrete in general, however, stood this trial exceedingly well in view of the protracted high temperature. The fire caught through an unprotected rear door in the southwest corner, and the break in the roof made possible a very hot fire, which melted glass and even welded nails. The concrete floors and the column protection were not damaged in the slightest. If the methods of fire protection had been consistent throughout, it is probable that this building would have escaped without damage.

POST-OFFICE BUILDING.

The writer made a thorough examination of the post-office building, on Mission street between Sixth and Seventh streets, in company with J. W. Roberts, superintendent of construction, of the Supervising Architect's Office. This three-story structure rested on a foundation consisting of steel beams incased in concrete, carried through the soft alluvium to a hard gravel, the depth varying from 30 feet at Seventh and Mission streets to 12 and 14 feet at the opposite corner. The building had a steel frame, expanded-metal and concrete floors, and plastered expanded-metal suspended ceilings. All partitions or interior walls were of terra-cotta hollow tile, laid with full joints of Portland-cement mortar, the terra-cotta work being first class in every particular. The corridors were tiled and wainscoted with marble. The exterior walls were of granite and were thoroughly anchored, each stone being fastened to the steel work and doweled and pinned to the adjacent stones. The outer facing of granite is carried on the steel work and is not backed with brick, there being an inner wall of terra cotta, with a dead air space between, which serves as a passageway for pipes, flues, etc.

The ground at the corner of Seventh and Mission streets settled about 5 feet (Pl. XLIII, *B*). The floor of the building was slightly cracked at that point, and Mr. Roberts stated that there was a settling of about 1¾ inches. The outer walls were considerably racked (Pls. XLIII, *A*; XLIV) by the earthquake, many stones having been shaken entirely loose from the steel work in some places, while in others a number of stones were started from their beds, and the anchorage was broken. There were also many cracks, especially in some of the exterior pilasters, which were formed of two steel columns, 12 feet apart, without diagonal bracing, the hollow space being used for heating and ventilating apparatus. These pilasters were badly racked.

The worst damage appeared to be in the interior walls of hollow tile, which were very extensively cracked, especially on the first and second floors. The plaster finish on the hollow-tile partitions strengthened them very considerably. One portion of the mosaic ceilings of the corridors on the main floor was laid in Portland-cement mortar on a flat tiled arch and was badly cracked; another portion, laid in Portland cement against wire lath plastered, was undamaged. In the mail-handling room the end wall was moved out of plumb by the earthquake, and the enameled-brick covering of several columns was shaken off. The only damage done by fire was in the district-court room, in the north corner of the third floor, which caught from without and was burned out, together with two adjacent rooms on the northwest front. On the northeast end of the first floor the exterior stonework was also spalled by fire.

A very considerable amount of damage was done by the dynamiting of near-by buildings, which was so severe as to smash the glass and blow out the window and door frames. In many places the marble wainscoting on the opposite side of the corridor was shaken loose. Probably 20 per cent of the injury done to the building is in the glass, marble, and finish. The building is substantial, and the materials and workmanship are first class.

RIALTO BUILDING.

The eight-story Rialto Building, at the southwest corner of Mission and New Montgomery streets, had a steel frame and reenforced cinder-concrete floors. The partitions were of hollow tile and the ceilings of suspended expanded metal, plastered. The columns were fireproofed with two layers of plastered expanded metal for all floors except the basement, where only one layer was used. The corridors had mosaic floors, and the stairways were of cast iron with marble treads.

The building was considerably racked by the earthquake and was further damaged by fire and dynamiting (Pl. XLVIII, *B*). The fire was only moderately hot, but was sufficient to destroy the fireproofing of two columns in the northeast corner of the basement, so that they failed by buckling (Pl. XLVIII, *A*), causing extensive wrecking of the upper floors. The failure of the column protection was caused by the expansion of a pipe inside of it. The terra cotta around the entrance to the building was cracked by the earthquake.

ST. FRANCIS HOTEL.

The twelve-story St. Francis Hotel, in West Union square, at the corner of Geary and Powell streets, was of a modern type, having a steel skeleton, reenforced-concrete floors, with suspended ceilings plas-

tered on wire lath. The fireproofing of beams and girders in the basement and first floor was concrete; in the upper floors it was wire lath and plaster. The columns of the first floor were fireproofed with concrete, those in the basement with brick, and on the upper floors 4-inch hollow tile was used. On the first floor the concrete was omitted for 18 inches at the top and a cap of plaster of Paris used; this was a serious mistake and might have caused trouble.

The stone was slightly spalled by fire and on the front was slightly damaged by the earthquake. The enameled bricks of the light well were badly spalled by heat. Two columns failed by buckling. The fire was not severe, and the damage was not very great.

SCOTT BUILDING.

The Scott Building, on the south side of Mission street between First and Fremont streets, was a four-story structure with a mansard roof. Machinery sales rooms occupied the two lower floors, printing and lithographing offices the upper. The building was constructed of steel girders and beams, with reenforced-concrete floors, suspended ceilings plastered on metal lath, and unprotected cast-iron columns. The curtain walls were carried on steel work which was unprotected over the windows.

The mansard roof and the upper part of the walls were destroyed by the earthquake. The western section was wrecked by dynamite. The ceilings failed, and the stonework spalled slightly. The fire was not severe, to judge from the appearance of the undamaged naked cast-iron columns.

SECURITY SAVINGS BANK.

The Security Savings Bank, a two-story building on Montgomery street between California and Pine streets, received its principal damage from the falling walls of an adjacent building. The granite and marble front was slightly spalled by the earthquake.

SHREVE BUILDING.

The eleven-story Shreve office building, at the northwest corner of Post and Grant streets, was constructed with steel frame, reenforced-concrete floors, and suspended ceilings plastered on metal lath. The columns above the second floor were fireproofed with 3-inch hollow tile; those below with concrete. This latter protection, as well as the concrete floors, is in first-class condition. The difference in efficiency between the concrete and hollow-tile protection for columns is clearly demonstrated, the former being in excellent shape, whereas the latter failed, resulting in a number of buckled columns.

SLOANE BUILDING.

The seven-story Sloane Building, on Post street between Grant and Kearney streets, had bearing walls of terra cotta, brick and terra-cotta trimmings, and a framework of cast-iron columns and steel beams and girders. The partitions and fireproofing were of expanded metal, plastered, and the floors were of concrete, reenforced with expanded metal. All columns except those in the basement were fireproofed with expanded metal, plastered.

There is every indication of a very hot fire in the basement, which buckled several of these unprotected columns, causing a collapse in the central portion of the building (Pl. XLIX, *A*).

SPRING VALLEY WATER COMPANY'S BUILDING.

The City of Paris Dry Goods Company occupied the two lower floors of the Spring Valley Water Company's building, at the southeast corner of Geary and Stockton streets, the remaining four stories being used for office purposes. The building, a general rear view of which is shown in Pl. L, *A*, had a steel skeleton, the partitions, column protection, and floor arches, the lower web of which spalled off extensively, being of hollow tile. The floor arches were topped with cinder concrete and covered with wood. The columns in the southeast corner of the basement buckled, and the upper stories collapsed. The hollow-tile partitions were in bad condition, and the 2-inch tile on columns failed generally. Where the tile ceilings were unprotected the webs spalled extensively; where there was a suspended ceiling remaining in position the tiles were in fair condition. The cast-iron stairways with marble treads were also damaged. There were a few slight earthquake cracks along the Stockton street side, and the south wall had a vertical crack.

UNITED STATES SUBTREASURY.

The four-story brick subtreasury building, on Montgomery street between Commercial and Clay streets, had rolling shutters on the lower front windows and a combination of wood and concrete floors. The wood burned, causing the collapse of that portion of the building. The remainder of the concrete-floor portion seemed to be in fair condition.

UNION TRUST COMPANY'S BUILDING.

The Union Trust Company's ten-story office building, on the corner of Market and Montgomery streets, was constructed with a steel frame. The front walls of the first two stories were granite; the

remaining walls were of pressed terra-cotta brick, with terra-cotta trimmings. The floors and partitions were of hollow tile, and the girders, beams, and columns were fireproofed with the same material. The floors were topped with cinder concrete covered with wood, except in the corridors, where cement finish was used. The cast-iron stairways had marble treads. The granite walls were spalled around the openings by fire. The hollow-tile partitions failed extensively, and the lower web of the floor tile spalled over large areas. The fire was not intense, and the steel appeared to be in fair condition except on the ninth and tenth floors. The extent of the damage can be seen in Pl. L, *B*, a view on the ninth floor. The steel trusses on the tenth floor were very much distorted by heat, owing to the failure of the hollow-tile fireproofing.

VOLKMAN BUILDING.

The lower floor of the Volkman Building, on the north side of Jackson street between Montgomery and Sansome streets, opposite the unburned block near the appraisers' building, was occupied by a branch of the post-office. The structure was surrounded on the sides and rear by completely gutted buildings, and its escape was probably due to its protected openings. The windows were glazed with wire glass and the sash and frames were metal covered. The rear doors were equipped with Kinnear rolling shutters. A few windows were so badly damaged that they will have to be replaced, but the building was only slightly injured, for the fire did not gain a foothold.

WELLS-FARGO BUILDING.

The six-story Wells-Fargo Building, on the northeast corner of Mission and Second streets, is devoted exclusively to Wells, Fargo & Co.'s express business. It has a steel skeleton, self-supporting walls, and reenforced-concrete floors. The ceilings are of plastered wire lath, as are also the hollow partitions and the fireproofing on the columns. The outside walls are of granite for the first two stories and pressed brick and terra cotta for the remaining stories. The openings into the air and light well were of metal frame, glazed with wire glass.

This building shows, especially in the Mission street front, the racking effect of the earthquake. The marble treads of the cast-iron stairways were considerably damaged by the fire, and the marble wainscoting of the corridors was thrown down by the earthquake. The window frames in the light well (Pl. XLIX, *B*) were warped by the fire, which also spalled the terra-cotta trim.

ASPECTS OF THE FIRE DISASTER.

The San Francisco fire, which lasted three days, was one of the greatest conflagrations of recent times. The loss by fire was greater than it should have been, by reason of the failure of the cast-iron water mains in the city; although the loss must necessarily have been great because of the character of the buildings, 90 per cent of which were frame. This disaster demonstrated that the lessons from the Chicago and Baltimore fires are still unlearned. The same faults in construction continue to be repeated. The only sure way to remedy grave defects of this character is to enact strict building laws which will compel an observance of the essentials for fireproof structures.

The conditions at San Francisco were unusual, and even had not the water supply failed it is doubtful whether they could have been controlled, for the reason that it would have been impossible for the fire department to handle efficiently so many fires at a time, especially as there were so many nonfireproof structures. Large conflagrations demonstrate that there is no such thing as a fireproof building. To label one as such is bad practice, since it gives a false sense of security and induces a relaxing of necessary precautions.

FIRE HISTORY AND RECOMMENDATIONS OF INSURANCE BOARDS.

It is claimed that the recorded destruction by fires in San Francisco up to 1899 was excessive, showing an average loss between two and three times that expected in cities having ordinary fire protection. In every year since 1899, except 1903, although the number of fires increased materially, the average loss per fire remained moderate. In any of these years the number of fires involving losses of $40,000 or more did not exceed two. In 1903 there were ten large fires, each involving a loss of more than $40,000, thus bringing the total up to a high figure; and at each of these fires the greater portion of the loss was to the contents rather than to the buildings.

In October, 1905, a board of fire-insurance experts presented the report of an examination made under the direction of the National Board of Fire Underwriters on the fire-hazard conditions of San Francisco. This report is extremely interesting and shows clearly how a body of trained experts can accurately locate defects and predict the consequences likely to result from them. The criticisms and recommendations embodied in the report are particularly pertinent to San Francisco; and when the conditions prior to the great fire are considered, the conclusion must be inevitable that no other result of these conditions—a general conflagration which swept the city—could reasonably have been expected. Attention was called to the following principal features of construction affecting the fire hazard

in the business district: (1) Bad exposures and unprotected openings; (2) poor construction; (3) an absence of sprinklers or of any of the modern protective devices; and (4) excessive height in nonfireproof structures. It is stated that in the congested district about 2.2 per cent were fireproof, 68.3 per cent were wooden joisted brick, and 29.5 per cent were frame buildings. A very bad feature lay in the fact that a large number of so-called "fireproofs" were surrounded by nonfireproofs. The mixture of dwellings and minor mercantile buildings surrounding the congested-value district also greatly increased the hazard.

The board recommended the municipal ownership of the water supply. They considered the present supply ample in amount for the existing requirements, but subject to a decided probability of local failure in emergencies, owing to faults in the distribution system. They deemed it very desirable to increase the capacity of the existing system and to install at the earliest possible date a separate fire-main system, and recommended that all dead ends of pipe mains be connected with the network wherever practicable. They advised that the system of distribution be equipped with a sufficient number of gate valves, so located that no single case of accident, breakage, or repair to the pipe system would necessitate the shutting from service of a length of main greater than the side of a single block (a maximum of 500 feet) in important mercantile manufacturing districts, or than two sides of a single block (a maximum of 800 feet) in other districts.

The building code was found to be satisfactory on the whole, but the board recommended that it be so amended as to limit floor areas, provide for the protection of exposed openings in fireproof buildings, and encourage the use of modern protective devices and constructions, such as sprinkler equipments, automatic fire doors, wire glass, etc. They recommended that prompt measures be taken to relieve the hazardous conditions in narrow streets by widening the streets or enforcing adequate window protection, or both, and advised that automatic sprinkler equipments be required in all buildings which by reason of their size, construction, or occupancy, singly or combined, might act as conflagration breeders. The potential hazard was considered very severe, in view of the exceptionally large areas and great heights of many buildings and of their highly combustible nature by reason of sheathed walls and ceilings, numerous unprotected openings and light wells, and the general absence of fire breaks, taken in conjunction with the presence of interposed frame buildings and the comparatively narrow streets. These numerous and mutually aggravating conflagration breeders, considered in connection with the almost total lack of sprinklers and general absence

of modern protective devices, and the prevailing high winds, made the probability feature alarmingly great.

They advised that the inadequate force of four building inspectors be at least doubled, and that the building laws be rigidly and impartially enforced.

They found the fire department to be an efficient force, well organized under an exceptionally competent chief, and though weak in powerful engines, otherwise fairly well equipped, the number of engine companies being particularly large.

In their report the board summarized the situation in San Francisco as follows:

> While two of the five sections into which the congested-value district is divided involve only a mild conflagration hazard within their own limits, they are badly exposed by the others, in which all the elements of the conflagration hazard are present to a marked degree. Not only is the hazard extreme within the congested-value district, but it is augmented by the presence of a compact surrounding, great-height, large-area, frame-residence district, itself unmanageable from a fire-fighting standpoint by reason of adverse conditions introduced by the topography. In fact, San Francisco has violated all underwriting traditions and precedents by not burning up; that it has not done so is largely due to the vigilance of the fire department, which can not be relied upon indefinitely to stave off the inevitable.

FIRE-RESISTING QUALITIES OF STRUCTURES AND STRUCTURAL MATERIALS.

The fire which has practically destroyed San Francisco has more than fulfilled this prophecy. The destruction was greater than in the Baltimore fire because the fire was hotter, owing, as has been pointed out, to the inflammable surroundings and the unprotected openings, and to the unchecked sway of the flames. The heat was so intense that sash weights and glass melted and ran together freely. In some places the edges of broken cast-iron columns softened, the tin coating in piles of tinned plate volatilized, even in the middle of the piles, and nails were softened sufficiently to weld together. (See also Pl. LI, *A*.) The maximum temperature, lasting for a few minutes in each locality, was probably 2,000° or 2,200° F., while the average temperature did not exceed 1,500° F.

Nearly all the so-called "fireproofs" were gutted and their contents destroyed, the fire damage done to these buildings being fully 60 per cent. The early collapse of protected steel frames owing to the failure of the fireproofing was of common occurrence. The extent of the damage to a building from fire can be determined only after the débris and wreckage have been removed and will then be found to be much greater than was at first supposed. This is particularly true of steel structures in which the effect of fire is partly hidden by the débris.

Of perhaps thirty fireproofs of good height with reenforced-concrete floors, all but two had steel frames. Steel beams and columns were generally protected with metal lath and plaster, cinder concrete, or terra-cotta tile. Practically all floor construction consisted either of hollow terra-cotta tile or reenforced concrete. Ceilings of light angles and metal lath, plastered, suspended from floors, served as additional means of fireproofing, by keeping the fire from coming into direct contact with the flooring material. Steel beams in many buildings had no protection, even where concrete filled, except this subceiling. The lower webs of floor tile came off to perhaps a greater extent than in the Baltimore fire. It is said to be impossible to procure a suitable hard-wood sawdust on the Pacific coast, such as is required in the manufacture of porous terra-cotta tile. The tile used is therefore denser and of poorer quality. The behavior of reenforced-concrete floors was most excellent.

Partition walls were in a very few buildings of brick. As a rule, however, they were either of 3-inch hollow terra-cotta tile or metal lath, plastered.

The matter of column protection is very important, as the number of failures in the San Francisco fire was particularly large, especially in the Fairmount Hotel (Pl. XXXIV). Unprotected cast-iron columns failed as a result of unequal expansion caused by the lugs. A few light cast-iron columns filled with concrete came through without damage, and at the Academy of Sciences (Pl. XXIV, *A*), as already described, cast iron failed around a concrete core, which carried the load. Brick-filled columns gave fair satisfaction, but concrete-protected columns afforded the best results. The question of fireproofing, however, is one of degree, being dependent on the intensity and duration of the fire. A column may be fireproofed sufficiently for an office building, but entirely too little for a warehouse; or a column which may be suitable for the upper stories may fail in the basement, as in the Kamm Building (p. 40). Again, the practice of running piping back of the fireproofing on columns, especially if the fireproofing is of hollow tile, is extremely bad. Many failures were caused by the expansion of such piping throwing off the terra-cotta tile. Concrete is probably the best fireproofing material, because, as shown by experience, its stiffness will enable it to support not only the steel within, if the latter is softened by the heat, but perhaps the structure itself. The following types of column protection were used in San Francisco buildings: (1) Plaster on wire lath, both single and double layers, the latter having a dead air space; (2) single terra-cotta tile; (3) concrete; (4) concrete covered with terra-cotta tile; (5) brick.

Of the fire loss, perhaps 75 per cent was in the trim and ornamental work. Inflammable woodwork in the corridors, doors, and windows proved a source of great loss, and should be eliminated for orna-

mental purposes. The behavior of the metal-covered woodwork in the Kohl and other buildings was satisfactory and immensely better than that of the naked wood. It is certain that a building may be finished and trimmed and even decorated with noninflammable materials. Although the additional security of such materials in case of fire does not appeal to owners and architects as compensating for their extra cost in comparison with wood or other inflammable materials, the building laws should nevertheless compel this type of construction.

The loss in ornamental stonework was particularly great, especially in the case of marble, which in many structures was completely calcined. Brickwork suffered most from the earthquake and least from fire, and sandstone splintered less than granite, which suffered severely, a number of badly spalled columns showing how futile this material is for other than ornamental purposes. Concrete proved superior to brick as a fireproofing medium.

It is estimated that over 80 per cent of the so-called "fireproof" safes failed. Many valuable records and much other property were thereby destroyed. An ordinary fireproof safe was of absolutely no value, and the contents of nearly every one were destroyed. In many office buildings so-called fireproof vaults were constructed of hollow tile or plastered metal lath, being formed partly by the partitions of the rooms, and were so flimsy that they yielded readily to the flames. In Pl. LII can be seen groups of so-called "fireproof safes," many with walls 20 inches or more thick, which failed to serve the purpose for which they were designed. Pl. LII, *B*, shows part of a collection of over 50 of these "safes" whose contents were destroyed. In a number of jeweler's safes silver and other precious metals were melted. The warping of the doors also resulted in the loss of the contents in many vaults, even where they were otherwise well designed. In short, fireproof vaults and safes behaved in the San Francisco fire very much as they did in the Baltimore fire. Little progress seems to have been made toward the production of a satisfactory fireproof safe. The only really fireproof vault is one with brick or concrete walls not less than 10 inches thick. The cement-filled metal safe proved to be a very good type of fireproof. Even in well-designed safes and vaults, great care must be exercised in opening them after they have been exposed to fire. Time should be allowed for the temperature in the interior to become reduced to somewhere near the temperature of the surrounding air, as otherwise the contents may be destroyed by spontaneous combustion on exposure to the air. Pl. LII, *A*, is a view of one of the oldest vaults in San Francisco, that of the old Wells, Fargo & Co.'s Express, which passed the fire test satisfactorily.

The writer is of the opinion that the present commercial hollow

terra-cotta tile is largely, if not entirely, devoid of merit for fireproofing purposes. Even when it is of the best grade and workmanship it can hardly be considered a first-class building material. At a comparatively low temperature the tiles fail, the thin webs spalling from unequal expansion. A more porous tile, with thicker webs keyed together and laid in Portland-cement mortar with tight joints, would unquestionably be more suitable for the purpose. It may be true that in case of repairs after a fire damaged tile of the usual commercial type can readily be detected and renewed. Terra-cotta tiling may, however, allow sufficient heat to pass through it to soften slightly the steel member which it encases and still remain in position, thus hiding the defect. Several examples of this condition were found.

The advocates of terra-cotta tile contend that concrete may be seriously damaged by dehydration without noticeable change in its appearance. While this contention may be justified, it should be noted that any weakness or softness may be as readily detected and repaired in concrete as in terra cotta. Concrete, moreover, has the great advantage of being a nonconductor of heat, and so will withstand a prolonged heat before the damage extends to any great depth; and it usually remains in place, maintaining its protective qualities. The value of a structure or of a method of fireproofing is determined largely by ascertaining what portion of the structure is left available for use after the fire. The word "fireproof" is of course a misnomer, for no building is absolutely fireproof; and the resistance offered to fire is one of degree only, for if the heat be sufficiently high and prolonged, nothing can withstand it. The best materials are nonconductors of heat, having high fusing points. At high temperature concrete loses its water of crystallization, but the depth to which this dehydration goes and the rate at which it takes place are the factors that determine the effectiveness of the material. The heat insulation afforded by concrete is of a high order, and to obtain the best results a sufficient thickness must be applied. This required thickness is naturally a variable quantity; 2 inches, or even 1 inch, may be sufficient for an office building, but would be inadequate for a warehouse. These remarks concerning concrete also apply to all other forms of fireproofing. The precise point on which information should be [illegible] is the thickness of the insulation for proper protection against fire.

[illegible] is that of protecting a building [illegible] means the protecting of all [illegible] equally as resistant as the other [illegible] should be self-contained—that is, [illegible] capable of fighting fire from the [illegible] where the outside water service

is likely to fail through rupture of the steel mains, it is highly desirable to have an independent supply, as from an artesian well, with the necessary pumps and service pipe.

In the matter of fireproofing, certain definite recommendations may be deduced from the San Francisco conflagration, as follows:

1. Exterior openings should be protected by the use of metal frames or metal-covered frames with wire glass, or exterior iron shutters or interior metal-covered shutters, or both exterior and interior shutters.

2. The structural members, especially the columns, should be better protected, preferably with solid concrete; they may be filled with brick and covered with terra cotta or with a double layer of cement-plastered metal lath, with an air space between.

3. There should be a better type of partition, the present plastered metal lath or hollow terra-cotta tile being inadequate. Reenforced-concrete partitions are much more efficient.

4. All combustible trim should be eliminated. The fire loss from this item is high, and it should be so designed as to be replaced readily and cheaply.

5. Attic floors and roofs should be designed to resist fire. In many buildings the roof members were not fireproofed and their failure caused great damage.

6. Buildings should be so arranged that the fire could be confined to a single room.

WATER SUPPLY AND OTHER METHODS OF FIGHTING FIRE.

In connection with the matter of the fireproof construction of buildings above referred to, certain suggestions may be made in regard to private and public facilities for fighting fire, as follows:

1. An independent water supply and other facilities for fighting the fire from either within or without should be provided.

2. Another very important problem, at least so far as San Francisco is concerned, is that of the public water supply. The failure of a gridiron system of cast-iron pipes seriously cripples a water supply, no matter how large may be the storage. It is also evident that greater care must be exercised in the laying of these mains, especially in filled ground or alluvial soil, where failures are likely to occur. A system of by-passes should be provided, so arranged as to permit the cutting out of portions which are broken or otherwise damaged, and some system should be installed for quick repairs under emergency conditions.

3. A high-pressure service operated from the bay, using salt water, would also be an essential feature. This service might necessitate a floating pumping station, as recommended by the National Board of Fire Underwriters.

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Perhaps the most important problem is that of protecting a building from fire from without. To do so means the protecting of all openings and the making of the roof equally as resistant as the other parts of the structure. Buildings should be self-contained—that is, protected against exterior fires and capable of fighting fire from the inside; and in earthquake countries, where the outside water service

is likely to fail through rupture of the steel mains, it is highly desirable to have an independent supply, as from an artesian well, with the necessary pumps and service pipe.

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3. A high-pressure service operated from the bay, using salt water, would also be an essential feature. This service might necessitate a floating pumping station, as recommended by the National Board of Fire Underwriters.

4. The use of explosives, such as dynamite, for fighting a fire should be greatly restricted and intrusted to experts only, or else abandoned. It is extremely doubtful whether the progress of a fire can be checked by dynamiting in advance of the fire without the removal or thorough wetting of the débris. Such procedure would have been impossible in San Francisco, as the water supply was unavailable and it was impossible to carry away the wreckage. The indiscriminate dynamiting did more harm than good, for the reason that the concussions injured the surrounding buildings, as shown, for example, by the extensive damage done at the post-office. Back firing would have been equally bad, because to apply this method successfully plenty of water for controlling the fire is necessary. A fire stop is the best way of checking a conflagration, and a fireproof structure makes the best fire stop if it has well-protected openings.

GENERAL LESSONS OF THE EARTHQUAKE AND FIRE.

In considering the results of the destruction which was wrought by the earthquake and fire there appear certain salient features from which conclusions may be drawn. In regard to the possibility of the erection of an earthquake-proof structure, it is apparent and universally admitted that it would be impossible to build on the fault line a structure which could withstand the effect of a slip. Furthermore, it is realized that in building near the fault on soft or alluvial soil extra precautions must be taken; for example, location of the San Francisco water mains in ground of this character was unwise, since it is difficult to design a waterworks system capable of resisting the effect of settling of the ground. The importance of proper construction and distribution of the water mains in districts liable to earthquakes is demonstrated by the fact that the greatest damage in San Francisco, fully 85 per cent of the total, was by fire. The action of the earthquake in starting the fires which grew to a great conflagration seems insignificant compared to the breaking of the water mains, which left the city defenseless against the flames.

The comparatively great destruction wrought by the earthquake to structures located on filled ground or alluvial soil has already been pointed out. The destruction in San Francisco was confined largely to buildings located on the alluvium of the flats or on the filled ground of old watercourses. That structures can be built, however, which will satisfactorily meet even such conditions when adequate foundations are provided, extending through the soft material to a solid base, is demonstrated by the behavior of such buildings as the Leland Stanford Junior Museum (Pl. XIV, *A*) and Roble Hall, at Stanford University; the Government buildings (Pls. XXVIII, *A*; XXXVIII; XLII, *B*; XLIII; XLIV), and the Call and other buildings in San Francisco.

The structures which suffered most from the earthquake were—

1. The municipal and county buildings. The greatest destruction was sustained by these buildings, which were generally badly designed and poorly constructed of inferior materials, while the well-built, substantial Government buildings suffered less.

2. Lightly and flimsily constructed wooden buildings. Well-constructed wooden buildings generally withstood the shock, but those that were flimsily built, resting upon posts or equally insufficient foundations, collapsed, even where they were fairly well designed. The essentials of earthquake-resisting power are vertical continuity, adequate diagonal bracing, and first-class foundations.

3. Improperly built brick and stone structures. The brick walls which failed, either by being shaken down entirely or by shattering, were laid in lime mortar with few header courses, and generally had wooden frames with little or no bracing and no tie to the walls. Stone and brick masonry cracked diagonally in the form of an X. Hollow-tile partitions and masonry of brick or stone were similarly cracked, although this injury was small where Portland-cement mortar was used. Where the walls were laid with hard brick, with plenty of headers and in Portland-cement mortar, and were properly tied to the floor and roof members there was little, if any, damage. Chimneys collapsed most generally, breaking about halfway up, and destroyed in part at least the structures upon which they fell. While the evidence was by no means conclusive, it appeared to the writer that brick stacks of circular section proved more substantial than square ones. The stack of the Valencia street power plant, which was of eight-pointed star section, collapsed, the part which remained standing showing cracks at one of two opposite reentrant angles almost to the base (Pl. LIII, *A*). It is quite evident that brick stacks and similar tall structures built of brick or stone without reenforcement against flexure, or without being guyed, are unsuitable for use in countries liable to earthquake shock. They should be constructed either of steel, guyed, or, if self-supporting, of steel or reenforced concrete. (See also Pl. XIII, *A*.)

4. Insufficiently braced and loosely constructed steel structures. In structures which were deficient in diagonal bracing the effect of the earthquake was localized in the piers between openings and curtain walls in characteristic X cracks. In tall structures like the Call Building, the tower of the Union Ferry Building, and others, the diagonal bracing that had been installed proved insufficient, and the diagonals at about the middle distance between the top and base were strained beyond the elastic limit of the material, acquiring a permanent set, which was indicated by a slight buckling. It is assumed that the effect of earthquake shock on diagonal bracing is equivalent to a heavy wind pressure, variously estimated at 30 to 50 pounds

per square inch. The writer believes that the higher figure should be used, because the essential in satisfactory earthquake-resistant design is rigidity, whereby the structure moves as a unit. Unless there should be earthquakes of greater severity than the one under discussion, no fear need be felt for tall buildings. It has been fully demonstrated that a steel frame well braced diagonally upon an adequate foundation successfully meets the earthquake requirements; not even the masonry being injured to any great extent.

Concrete, especially reenforced concrete, because of its great adhesive strength and reenforcing metal, proved more satisfactory than any other material. Its solid monolithic structure produces a successful earthquake-resisting material, inasmuch as it moves as a unit; moreover, it offers a maximum resistance to fire. The great concrete dam of the Crystal Springs Lake at San Mateo (Pl. XI, *B*) gave abundant proof of the substantial qualities of concrete in a mass, for although it lies within a few hundred yards of the fault, it suffered no damage. Solid concrete floors proved satisfactory, though concrete in San Francisco was of a very poor quality, and flimsy concrete stiffened with light metal passed as reenforced concrete. Cinder concrete was used extensively for floors and elsewhere, and was of a very inferior grade. Much of it was high in sulphides, which had a deleterious effect on the embedded material, especially in floors where slight cracks permitted air and moisture to come in contact with these sulphides and the metal. For a proper earthquake-proof structure, everything—the design, the materials used, and the workmanship—must be first-class. Most of the failures resulted from bad design, poor workmanship, and poor materials. If reenforced concrete of the quality described could give such satisfactory results in meeting the extraordinary conditions of the San Francisco earthquake and fire, it is evident that much greater satisfaction would have been given by the use of first-class material.

The causes of the failures in San Francisco may be summarized as follows:

1. The effort on the part of those qualified to design and advise on building construction to meet the owners' demands by planning structures so that they can be erected for the least possible cost, a practice which tends to a departure from the principles of correct design, the result being a structure that will carry ordinary loads, but that fails when subjected to unusual conditions. Such was the case at Stanford University, where the poorly constructed stone-veneered buildings met ordinary conditions, but failed in the earthquake; while the more substantial structures, like the dormitories—one of reenforced concrete and the other of solid stone masonry—survived.

2. Actually dishonest design and construction.

The following requirements should be adhered to in structures for earthquake countries:

1. Location on or near the fault should be avoided.
2. Foundations and superstructures should be so built that they will move as a unit.
3. Wooden structures should be rather heavily framed, with continuity in the vertical members, adequate diagonal bracing, and substantial foundations.
4. Steel structures should rest upon an adequate foundation and be thoroughly braced diagonally. This feature is a most important one, as rigidity is absolutely essential.
5. Brickwork and stonework should be thoroughly bonded with full header courses laid in Portland-cement mortar.
6. Masonry should be thoroughly tied to the steel or other framing members.
7. Buildings should have no unnecessary material in their superstructures, and heavy ornamentation should be omitted.
8. Flimsy floors and partitions should be avoided; reenforced concrete is an excellent material for both.

Professor Omori, chairman of the Japanese earthquake commission, and other earthquake authorities, have stated that great earthquakes are followed by a settled condition in the earth's surface and that there is an interval of fifty or one hundred years during which no earthquakes occur. The general fear which prevailed during the first days following the earthquake has been quieted by these assurances, which have also created a feeling of security that has led to a relaxation of the precautions necessary in the work of reconstruction. The lessons taught by the great calamities such as have befallen San Francisco, Baltimore, Chicago, and other cities are not regarded. It is very probable that the new San Francisco to rise on the ruins will be, to a large extent, a duplicate of the former city in defects of construction.

OBSTACLES TO RECONSTRUCTION OF SAN FRANCISCO.

The actual loss by fire in San Francisco was much greater than in the Baltimore fire, for the reason that many insurance companies have taken advantage of the earthquake clause in the policies and failed to pay their claims, while others without the requisite funds were unable to pay the large claims in full. This failure to pay a very considerable percentage of the fire losses and the delay in adjusting them have proved serious setbacks in the progress of reconstruction.

The new building code is also operating against the best interests of the city. The arbitrary classification of buildings based on the

type of construction is one which will result in more harm than good. Those interested in its preparation directed their attention principally to office and other large buildings, apparently not realizing that the greater proportion of reconstruction will consist of small three or four story buildings. The fact that a structure is built of steel and fireproofed does not make it superior to those representing other types of construction, for poor materials and workmanship may produce inferior quality, whatever the type.

The proposed code discriminates against reenforced-concrete buildings in designating them as class B structures. While not intentional, this conveys the impression that such buildings are next in order of superiority to structures of class A. Class A should embrace buildings so well designed and constructed of such first-class materials that they afford the maximum resistance to fire, and should represent the best method of fireproof construction regardless of type.

That there was only one reenforced-concrete building of the modern type in San Francisco was due in part to the opposition of the labor unions. The exorbitant demands for wages, coupled with the high cost of materials, have proved a serious handicap. The cost of all construction work is excessive at the present time, and business interests will suffer from the shrinkage in value which will follow the fall in price of labor and materials. This policy of the labor organizations is materially interfering with and checking the work of reconstruction.

In addition to these labor difficulties, the questions of widening and extending old streets and opening new ones, for the purpose of carrying out the plans for the new and greater city, are still undecided, and most of the business men are unwilling to begin the work of reconstruction until these points are settled.

STATISTICS AND GENERAL INFORMATION.

The defects of construction which are so strongly condemned by reason of the failure of the structures were no worse than those generally existing throughout the United States. The same defects are common, and it is evident that the same result would follow an earthquake of equal intensity in another part of the country. A moment's consideration will show that the loss of life and property in New York, for example, under similar conditions, would be enormous. The damage to property in San Francisco is estimated at $250,000,000, but this sum, large as it is, is exceeded by the total annual expenditures for new construction in New York.

The loss of life from earthquakes is usually very great. That it did not exceed 500 in San Francisco is explained by the fact that at the time of its occurrence, during the early hours of the morning,

most of the inhabitants were in houses, 90 per cent of which were of frame. Structures of this type withstood the earthquake shock particularly well, which accounts for the minimum loss of life. Had the earthquake occurred four or five hours later, when the people were performing their daily tasks, in offices, schools, etc., or on the streets, the loss of life must have been very great. The writer saw a view of a drove of cattle buried under the ruins of a fallen wall while passing through Mission street, which graphically told the story of what might have occurred had the shock come later in the day. Although the loss of life was small, more than 200,000 people were rendered homeless and dependent on the authorities for even the necessaries of life.

In three days the tremendous area of more than 2,593 acres was burned, destroying entirely 490 city blocks and in part 32 blocks. (See Pls. LIV–LVII.) Of this area, 314 acres constituted the congested district, on which there was $250,000,000 insurance, probably representing a value of at least $500,000,000.

In the Baltimore fire (February, 1904) 1,343 buildings were destroyed, having an assessed value of $12,908,300. In two years these burned buildings were replaced by 570 buildings, whose assessed value is $20,000,000. These new buildings are larger than the old, and the widening of the streets has eliminated 700 building lots. It is expected that when the reconstruction within the burned district is complete there will be fewer than 800 buildings, of which the assessed value will be fully $25,000,000. It is therefore quite reasonable to suppose that the assessed value of the reconstructed San Francisco will be at least double that at the time of the catastrophe.

THE EFFECTS OF THE EARTHQUAKE AND FIRE ON BUILDINGS, ENGINEERING STRUCTURES, AND STRUCTURAL MATERIALS.

By JOHN STEPHEN SEWELL.

INTRODUCTION.

SCOPE OF THE INVESTIGATION.

The following pages contain the matter of a report dated July 5, 1906, to Brig. Gen. Alexander Mackenzie, Chief of Engineers, United States Army, of an inspection made by me of the ruins of San Francisco, in accordance with Special Orders No. 97, dated War Department, Washington, April 23, 1906.

I arrived in San Francisco on the morning of May 8, 1906, and remained until the night of May 19. My orders directed me to investigate the effect of the fire and earthquake on buildings and engineering structures in the territory affected by the earthquake, and authorized me to visit such points in addition to San Francisco as it might be necessary to observe. As soon as possible after my arrival, I called on the various military and civil authorities, and procured from the latter permits authorizing me to enter and inspect the damaged structures.

It appeared that in the territory affected by the earthquake, in addition to buildings of various types, there were the works of the Spring Valley Water Company and fortifications, light-houses, and railroad structures. Some rumors of collapsed tunnels on the coast division of the Southern Pacific Railroad had been circulated in the East before I left Washington. I found on inquiry, however, that no tunnels had collapsed, and whatever damage had been done, except to buildings along the line, had been wholly or partly repaired before I reached California.

Inquiry among engineers and others competent to speak disclosed the fact that the dams of the Spring Valley Water Company were practically not injured by the earthquake. Considerable damage was done to some of their conduits and to the pipes of the distribution system. Inquiry in reference to these items disclosed the fact that a

personal examination would consume a great deal of time. It also disclosed the fact that an examination was in process by competent engineers, and Major McKinstry undertook to get for me a report of the results of this examination. As a matter of fact, I have been allowed to see a copy of such a report made by Charles D. Marx and Charles B. Wing, which the authors prefer not to have published as yet. However, certain essential facts as to the condition of dams, conduits, etc. (see Pls. IX; X, *A;* XI, *B*), are taken from it and embodied further on in my own report; although the photographs and certain other features of the report itself, which seem to be peculiarly the property of its authors, are not submitted herewith. In view of the fact that the results of the examination of the waterworks were promised to me, it seemed superfluous for me to visit the dams and conduits, except as a matter of personal interest, and as my time was very short, I decided not to do so.

The light-houses and fortifications are in charge of competent officers, whose duty it is to report the nature and extent of the damage done to them by the earthquake. As an inspection of the light-houses would have involved a great deal of time, I decided not to attempt to visit them, and made only a superficial examination of the fortifications.

As my own experience has been mainly in the line of fireproof buildings, however, I made a very careful inspection of the ruins of San Francisco itself, and also visited Oakland and Palo Alto, with a view to inspecting damaged buildings at those points. I found, as a result of those trips and by inquiry among competent witnesses, that, with one exception, there was no type of building in the affected district which was not well represented among the buildings of San Francisco. The exception was the concrete work at Leland Stanford Junior University, near Palo Alto, to which specific reference is made on page 113. The greater part of my time, for the reasons above outlined, was spent within the limits of San Francisco itself, and much of it within what had been the congested district of the city.

ACKNOWLEDGMENTS.

Acknowledgment is due to Capt. M. L. Walker, Corps of Engineers, commanding officer at Fort Mason, who not only entertained me at his quarters during my stay in San Francisco, but rendered very material assistance in the way of transportation when needed, and especially in placing at my disposal the services of Private William H. Hughes, of the First Battalion of Engineers, a very efficient photographer, who accompanied me and took such views as seemed desirable for the purposes of my report. I was also much indebted to Maj. C. H. McKinstry, Corps of Engineers, who gave me much

valuable information that made it possible to avoid useless expenditure of time, and who was also of great service in procuring for me the necessary permits from the local civil authorities.

EXTRACTS FROM THE REPORT OF A COMMITTEE OF THE NATIONAL BOARD OF FIRE UNDERWRITERS ON SAN FRANCISCO CONDITIONS.

San Francisco before the earthquake and fire consisted mainly of frame and brick buildings of ordinary construction. A few adobe buildings still remain, but there were not many of these. There were about 45 so-called fireproof buildings in the city, and a small number of so-called slow-burning buildings, modeled more or less loosely along the lines of the New England mills. A fair idea of the general nature of the city, so far as buildings are concerned, is given in the following quotations from a report on San Francisco issued by the committee of twenty of the National Board of Fire Underwriters in October, 1905:

CONFLAGRATION HAZARD.

Potential.—In view of the excessively large areas, great heights, numerous unprotected openings, general absence of fire breaks and stops, highly combustible nature of the buildings, many of which have sheathed walls and ceilings, frequency of light wells, and the presence of interspersed frame buildings, the potential hazard is very severe.

Probability feature.—The above features, combined with the almost total lack of sprinklers, and absence of modern protective devices generally, numerous and mutually aggravating conflagration breeders, high winds and comparatively narrow streets, make the probability feature alarmingly severe.

Summary.—While two of the five sections into which the congested-value district is divided involve only a mild conflagration hazard within their own limits, they are badly exposed by the others, in which all the elements of the conflagration hazard are present to a marked degree. Not only is the hazard extreme within the congested-value district, but it is augmented by the presence of a compact surrounding, great-height, large-area, frame-residence district, itself unmanageable from a fire-fighting standpoint by reason of adverse conditions introduced by the topography. In fact, San Francisco has violated all underwriting traditions and precedents by not burning up; that it has not done so is largely due to the vigilance of the fire department, which can not be relied upon indefinitely to stave off the inevitable.

In another portion of the same report the following occurs:

The principal features affecting the conflagration hazard in the business section are bad exposures, poor construction, lack of proper protective devices, excessive height in nonfireproof buildings, large floor areas, and the large percentage of frame construction present.

The mixed dwelling and minor mercantile section which immediately surrounds the congested-value district, and extends from it in all directions with more or less uniformity, is alarmingly compact.

* * * The security resulting from a combination of redwood and such dampness as exists in San Francisco is regarded by the national board engineers as fancied merely.

In addition to the frame, ordinary joisted brick, so-called fireproof, and mill buildings, there were in San Francisco four buildings of a monumental type, so far as weight of construction was concerned. These were the new city hall (Pl. XXXI), the new post-office building (Pls. XLIII and XLIV), the United States mint (Pl. XXXVIII), and the appraisers' stores, or custom-house (Pl. XXVIII, *A*). The few mill buildings which existed were not of a standard type, according to the report of the National Board of Fire Underwriters. The fireproof buildings had been erected in accordance with the building laws of San Francisco, which provided for three principal types of commercial buildings, known as class A, class B, and class C.

The general requirements for buildings of these classes and for mill buildings are as follows:

BUILDINGS IN FIRE LIMITS.

SECTION 96. Every building hereafter erected within the fire limits shall be constructed in accordance with the requirements of this ordinance for the construction of buildings of either class A, class B, or class C.

BUILDINGS OF CLASSES A, B, AND C.

SECTION 97. Class A, termed "fireproof," or "skeleton construction," shall include all buildings wherein all external and internal loads and strains are transmitted from the top of the building to the foundation by skeleton or framework of steel, and the beams or girders of which are riveted to each other at their respective juncture joints. A building of this class must be constructed of noninflammable material throughout, and all interior constructive metal work, with the exception of the framing for elevators and staircases, shall be protected from fire by brick or terra cotta at least 1½ inches thick, or by plastering three-fourths of an inch thick applied to metal lath. The face of the plastering shall be 1½ inches from the metal. Wood may be used only for window and door frames, sashes, standing finish, hand rails for stairs, and for the upper and under floors and their necessary sleepers. Wood may also be used for isolated furring blocks, but this class shall not permit the use of laths or furrings of wood.

Class B. A building of this class shall be constructed with all its exterior walls and piers of masonry, or of masonry and steel, and all exterior surfaces other than masonry shall be covered with noninflammable materials. All partitions, furred walls, or other plastered surfaces throughout shall be metal lathed. All interior metal work shall be protected as in class A, and in addition the floor and ceiling joists, posts, roof boards, and partitions may be of wood in such places as does not violate the requirements of any section or clause of this ordinance.

Class C. A building of this class shall be constructed the same as class B in every respect, except as to the requirements for interior lathing.

SECTION 98. Limit of height of buildings of classes A, B, and C:

	Feet.
Class A, limit of height	220
Class B, limit of height	100
Class C, limit of height	82

(As amended by Ordinance 1297.)

SLOW-BURNING OR "MILL" CONSTRUCTION.

SECTION 99. A building of the slow-burning or "mill" construction type is a building whose outside walls are built of masonry, concentrated in piers or buttresses, between which is a thin wall containing the door and window openings, and whose floors and roof are constructed of heavy timbers, covered with plank of a suitable thickness; the girders being supported between the walls by posts.

SOME FEATURES OF THE EARTHQUAKE AND FIRE.

AMOUNT OF DESTRUCTION DUE TO THE EARTHQUAKE AND FIRE, RESPECTIVELY.

Within the burned area all frame buildings and practically all buildings with timber floors were totally destroyed, with all their contents. This classification includes mill buildings and those of every other type in which the floor construction is combustible. Practically all the so-called fireproof buildings were gutted, and their contents were a total loss. The average loss on the buildings of class A was, in my judgment, considerably in excess of the average loss on the "fireproof" buildings in Baltimore. This statement can not be made with absolute positiveness, however, in the absence of a detailed estimate of the cost of repairing each building, which I had not time to make. I am quite sure, however, that the damage in San Francisco was greater than it was in Baltimore.

From what was left of the ruins themselves, and from the testimony of competent observers, including engineer officers who were ordered into the business district of San Francisco immediately after the earthquake and before the fire had destroyed the evidences of earthquake damage, I think it is quite certain that the earthquake damage was extensive and severe. There were no available data on which to base an accurate estimate, but I formed a general impression that the damage done by the earthquake alone was at least as great as 10 per cent of the total damage by fire and earthquake combined. The damage from the earthquake, however, was localized in a remarkable degree. In places a group of buildings were almost totally destroyed, and buildings almost in contact with them on all sides escaped practically without damage, although I feel quite sure that many of the wrecked buildings were superior in every way to their neighbors which escaped. Owing to the remarkable variation in the intensity of the shock from point to point, thus demonstrated, the measure of damage done to an individual building is by no means a measure of the excellency or inferiority of its construction. Some specific evidence on this point is presented elsewhere in this paper.

FIRE-FIGHTING OPERATIONS—THE USE OF DYNAMITE.

The fire, of course, completed the work begun by the earthquake. (See Pls. LIV–LVII.) The interruption of the water supply, due

to the breaking of the conduits and mains, left the fire practically in control of the situation. Some attempts were made to stop its progress with dynamite, but from what evidence I was able to obtain I doubt very much whether a great deal was accomplished by this means. It is probable that at one or two points where the fire had become much less fierce its progress was entirely stopped by the use of dynamite, but even this much is not certain. I am personally of the opinion that dynamite might be used so as to check the progress of a conflagration, but it has never been properly applied to that purpose as yet. It seems probable that if a strip of property, a whole city block in depth, extending across the entire front of the fire, were selected sufficiently far in advance to enable it to be completely razed by dynamite before the fire reached it it would prove an effectual barrier, especially if there were water available to keep the ruins thoroughly wet. In the absence of the water the only way to make sure of the result would be to have an enormous number of men ready, as soon as the buildings were demolished, to move the débris to the side nearest to the approaching fire. It is probable that the ruins would be set on fire by the dynamite itself, but with a sufficient number of men, properly handled, the amount of combustible matter along the side next to unburned property might be so materially reduced that the fire would not be able to cross the gap. I rather think that unless such heroic measures are applied the use of dynamite is just as likely to do harm as good in resisting the advance of a conflagration. It will readily occur to anyone at all familiar with such things that to get together the requisite number of men and properly direct their work would require full military control of the situation; otherwise the measures described, while not impossible, would hardly be practicable.

One or two attempts were made, apparently with not a great deal of judgment, to dynamite steel-frame buildings that were on fire. I understand that the explosive was simply placed in the basement loose, practically without any tamping, and detonated. The only result was to knock a few basement columns off their foundations and bring down a portion of the floor construction above. I doubt whether any good results could be obtained by trying to dynamite a steel-frame building as a means of stopping the advance of a fire. If, in a strip of property such as that described above, any steel-frame buildings exist, especially if the frames are protected with any sort of fireproofing, it is probable that more good would result from allowing them to stand, while dynamiting their combustible neighbors.

It would be practically impossible in the time available to demolish a steel frame so completely that all of the combustible débris could be properly handled. It would burn more freely and more disas-

trously after dynamiting than if the building were left intact. A good plan in such a case would be to remove all the combustible contents of the building before the fire reached it, throwing them out, if no other course were open, on the side next to the advancing conflagration. Under such circumstances the average fireproof building, while it might be ruined itself, would probably act as a barrier to the spread of the flames beyond it, although, of course, it could not prevent the fire from working around the sides if neighboring combustible buildings were not removed.

A certain amount of damage in addition to that caused by the fire and earthquake was done in San Francisco by the dynamite used to blow down dangerous walls. More specific data on this point are presented in the detailed descriptions.

TEMPERATURE OF THE BALTIMORE AND SAN FRANCISCO FIRES.

The apparently more complete destruction by fire at San Francisco than at Baltimore immediately raises questions as to the probable temperature of the San Francisco fire. I noted everything coming under my observation which would seem to give an idea as to the probable temperature prevailing, and I am personally of the opinion that the San Francisco fire was appreciably hotter than that at Baltimore. Thus, in places which had been occupied by hardware stores I saw kegfuls of nails with the wood all burned away, but with the nails still standing up in a compact mass, retaining the shape of the keg, owing to the fact that they had been partially welded together. In other places kegfuls of nails which had evidently fallen at least one story, and possibly several stories, into the basement of an adjoining building, had nevertheless retained the form and size of the keg, although some of the nails were loosened. I also saw a number of cast-iron radiators that were partially melted and some cast-iron soil-pipe fittings that had been melted to such an extent that it was not possible to tell what sort of fittings they had been. In some cast-iron columns which had been softened and broken in the fire the raw edges of the break were appreciably rounded and blunted, due to the incipient fusion of the metal. In the basement of an iron warehouse I saw a number of racks of steel bars which had apparently been precipitated from the first floor and which were to a considerable extent welded together. The weld was not perfect, of course, but at some of the points where the welds occurred it would have been impossible to separate the bars without considerable damage.

Glass of all kinds melted and ran freely. Lead sash weights melted and ran out of the window boxes before the timber of the boxes was entirely consumed. Several witnesses, among them an engineer officer, told me that they had observed this phenomenon in a number of places. The sheet-metal cases of typewriters and similar articles of

sheet metal, though they showed no evidence of melting, had been almost completely burned up, so that they were full of holes, and the metal itself presented the same appearance as iron that had been burned in a blacksmith's forge. In the warehouse of the Waterhouse & Lester Company, on Howard street, some racks of steel bars were precipitated into the basement when the building collapsed. These bars were partially welded together by heat. (See also Pl. LI, *B*.) In the ruins of glassware and china stores the glass, as a rule, was completely melted, and many articles of porcelain ware had become softened and distorted in all manner of shapes, indicating a high temperature, as porcelain is made of very refractory material.

All things considered, I am inclined to think that temperatures considerably in excess of 2,000° F. were not at all uncommon in the San Francisco fire, although there were manifestly, in the burned area, places where no such temperature was reached. Very few office buildings were subjected to such intense heat, except here and there in individual rooms, where there was evidence of the storage of records or other combustible matter in large quantities; but the department stores, dry goods stores, and other buildings of mercantile occupancy evidently suffered from temperatures at least as high as 2,000° F. In mercantile buildings these high temperatures seemed to be the rule and not the exception.

EARTHQUAKE- AND FIRE-RESISTING QUALITIES OF STRUCTURES AND STRUCTURAL MATERIALS.

EFFECT OF FIRE ON GOVERNMENT AND "CLASS A" COMMERCIAL BUILDINGS.

So far as resistance to the fire is concerned, the only buildings that presented anything of interest were naturally the monumental public buildings and the commercial fireproof buildings of the better class; that is, practically of class A. The fire did not succeed in entering the mint nor the appraisers' stores. It got into the upper story of the new post-office building at one corner, and cleaned out a court room and its adjoining offices; but it was held at this point, and the post-office building itself was not involved in a fierce conflagration such as that which ruined many of the commercial buildings. The fire got into the new city hall, and succeeded in wrecking the portion which was not ruined by the earthquake.

VAULTS AND SAFES.

In many of the office buildings in San Francisco suites of offices were equipped with vaults, some of which were fairly capacious and provided with doors of more or less efficient appearance, a number of them having the ordinary vestibule, with both inner and outer doors. Where the interior partitions of the building consisted of metal

furring, lathing, and plaster, the walls of the vaults were likewise of these materials. Where the interior partitions consisted of hollow tile, the walls of the vaults were of hollow tile also. Although I examined a great many, I did not see a single vault partitioned off either with metal lathing and plaster or with hollow tiles that preserved its contents. I was informed by some gentlemen, who were apparently connected with the Spring Valley Water Company, that on the top floor of their building a vault walled off with hollow tiles had protected its contents, but that the corner of the building in which it was situated had not been completely gutted, so that the vault did not receive a severe test.

In the Baltimore fire there were a number of vaults walled off with hollow tiles, and all that I happened to see during my inspection of the ruins in Baltimore had failed. The same thing was in evidence everywhere in San Francisco, and it is my opinion that this result could have been predicted with absolute certainty at the time these vaults were built, from data then available. To all external appearances, no doubt, the vaults looked like secure places in which to keep valuables; as a matter of fact, they were the flimsiest kind of shells, not capable of resisting any sort of determined attack from either fire or burglars. The tenant would have been better off without the vault, for in that case he would probably have carried his papers to some other point where they would have had a better chance to escape the fire.

The only vaults I saw that came through a really fierce fire without damage were those built of brickwork (Pl. LII, *A*). Even these vaults did not always protect their contents, however. I saw a number of them opened in which the contents had been totally destroyed. As they seemed to be fairly good vaults, this result was a matter of more than ordinary interest. I therefore carefully examined a number of them and discovered that the fire had gained access through cracks due to settling, or to the earthquake, or else through unfilled joints, due to poor workmanship in the original construction of the vault. It appeared that probably the contents of the building were burning fiercely around the vault before the floor above had burned out or collapsed, so as to give full vent to the gases of combustion. Some pressure must have been generated by the great heat thus confined, and under this pressure the incandescent gases resulting from the fire found their way through the smallest and most tortuous passages in the brickwork. In several cases it was apparent that the contents had probably been ignited by a small tongue of flame (probably not thicker than a lead pencil) penetrating into the vault as a result of such conditions.

A few vaults failed owing to the fact that the outer door warped and pulled away from the frame. Whether this warping could have

been prevented with an adequate number of bolts I do not know, but in an important vault it would seem worth while to have the outer door at least filled in the same manner as the door of a fireproof safe. If it were built in this way it would probably not warp—at least not enough to let the fire in.

To judge from the safes which I saw opened, very nearly three-fourths of the safes in the San Francisco fire failed to protect their contents (Pl. LII, *B*), and as a result the loss of valuable papers and records must have been very extensive.

BEHAVIOR OF STRUCTURAL MEMBERS AND MATERIALS.

The commercial fireproof buildings in San Francisco, in my judgment, suffered considerably more damage than corresponding buildings in the Baltimore conflagration. In the San Francisco fire, for the first time, the collapse of protected steel frames, due to the destruction of the fireproof covering at a comparatively early stage in the fire, was a matter of common occurrence. Practically all of the floor construction in fireproof buildings in San Francisco consisted either of hollow terra-cotta flat arches or of reenforced-concrete slabs, carried on steel floor beams. In a few buildings steel columns and girders were used, with reenforced-concrete beams and slabs covering the space between the girders. Steel girders were more generally protected with metal lathing and plaster, or with solid concrete filling, than with anything else, but terra-cotta covering was also used to a considerable extent. The lower flanges of beams were in some buildings unprotected; in others they were covered with metal lathing and plaster; and in still others (a rather general practice), there was a ceiling composed of light furring angles and metal lathing, fastened below the floor construction and plastered. Most of the steel beams and girders in the floor construction had no other protection for their lower flanges than this furred ceiling, even where the webs were protected by a solid concrete filling.

Columns were generally protected in one of three different ways, as follows:

1. With hollow tiles adapted to either a circular or square section, the webs being about five-eighths of an inch thick, and the total thickness of the tile, including webs and hollow space within, being about 2½ or 3 inches. The tiles were from 12 to 18 inches in length and about 12 or 15 inches wide.

2. With metal lathing and plaster surrounding the column, so as to leave an air space of about 1 or 1½ inches.

3. With a solid covering of concrete from 2 to 4 inches thick.

In addition to this protection the columns in the walls were generally covered with 4 inches of brickwork, and in one building there was a double covering of metal lathing around isolated columns, the

inner covering having one coat of plaster applied and the outer covering having the full two or three coats required for the finishing, as the case might be.

In a general way, practically none of the column protection in San Francisco, except the 4-inch brick covering, was adequate. The coverings of terra cotta and of metal lathing and plaster failed absolutely. Although there were a great many individual columns protected with other coverings which suffered only small damage, the number in which the protection completely failed was so great that the statement is entirely justified that practically all the coverings were wholly inadequate to resist any real fire test. The wall columns covered with 4 inches of brickwork were, except in one building, fairly well protected, so far as I was able to determine. None of the columns covered with cinder concrete suffered any serious damage, but there were not many columns protected in this way. Of the three buildings in which I particularly noticed such covering, two had evidently not experienced any great heat. In the third a column covered with 4 inches of cinder concrete had undoubtedly been subjected to a heat that was very intense. The concrete covering was seriously damaged; the column, however, had not suffered. This case is described on page 79.

Interior partitions in San Francisco were built almost entirely of hollow tiles similar to those used for making square coverings on columns, or else of light metal studs covered with metal lathing and plaster. A few were built of brickwork. In a general way it may be said that practically all the interior partitions that were not built of brickwork were a total loss, being absolutely inadequate. In my judgment, the burning of the contents of a single well-filled office room would have developed in the majority of buildings enough heat to get through the surrounding partitions.

The furred ceilings already described were also very largely a loss. In buildings that had been occupied for ordinary office purposes, probably not more than 20 per cent of the furred ceilings absolutely came down; the remaining 80 per cent stayed in place, with complete loss of the plaster, the metal furring and lathing, however, being in shape to use again with only minor repairs. But wherever the amount of combustible matter was evidently greater than that ordinarily found in offices, the entire furred ceiling—metal lathing, furring strips, and all—came down bodily and was a total loss.

So far as I was able to determine, the earthquake did not cause the collapse of any of the floor construction or partitions in any of the fireproof buildings, but it must have shaken a good many of the partitions badly, so that their destruction by fire was rendered somewhat more easy. The earthquake damage, however, only hastened the result. Partitions of the kind that were used in San Francisco

are not fireproof, and a very hot fire will invariably destroy them, notwithstanding the fact that they are made of noncombustible material. I had rather expected to find that some damage had been done by the earthquake to floors made of hollow tiles or brick arches. That no such damage occurred was a matter of some surprise, and indicates that the vertical component of the undulation was not very great. It is probable that the earthquake caused some cracks to appear in the floors, but I did not see any which could with certainty be ascribed to this cause. It was also a matter of some surprise that some of the partitions were not shaken down by the earthquake, considering the ease with which the fire destroyed them.

So far as fire damage was concerned, the floor systems in San Francisco stood better than any other portion of the fireproof buildings, although they did not stand very well, at that. The lower webs came off from the hollow-tile floor arches in the same way that they did at Baltimore, but to a very much greater extent. The cinder-concrete floor slabs in many buildings were protected for a time by the furred ceilings previously described. Where the ceilings failed at an early stage, or where there had been no such ceilings, the damage to the concrete floor slabs was very apparent. The concrete was dehydrated to a certain extent on its lower surface, and in many of the slabs the reenforcement had become so hot that there was a permanent deflection of greater or less extent, accompanied by cracks on the lower side in the middle of the span.

Just how much damage was done by the fire to cinder-concrete slabs was a little difficult to determine, for the reason that most of the cinder concrete used in San Francisco was evidently a very inferior article in the first place. There was no doubt in my mind, however, that the concrete near surfaces which had been exposed to the fire showed deterioration, as compared with that which had not been exposed to the fire, although it was all so poor that there was not much room for difference in quality. I saw reenforced-concrete floor slabs, some of cinders and some of stone, which were on the point of collapse from heat alone, although they had not quite let go.

I also saw a number of terra-cotta floor arches which had totally collapsed. Some of these showed evidence of damage by masses falling from above, but in others the collapse seemed to have been due to heat alone.

Girder and beam protection was a little more efficient than the column coverings, but it was not adequate. Its weakness was not fully developed, because, in many places where the necessary heat existed, the columns failed first and let down the floors, so that it was not possible to say how much of the damage to the floor members was due to heat alone. In a general way, however, it may be said that girder coverings of metal lath and plaster were wholly inade-

quate, those of hollow tiles suffered serious damage, and those of solid concrete failed a little more commonly than they should, although they were the best of all. Many girders that had been covered with metal lath and plaster were badly warped and deflected, and some wholly collapsed, from the heat alone. Many beams were seriously deflected from the heating of exposed lower flanges.

I was not able to learn that any serious damage had been done to column coverings by the earthquake. In some buildings columns which had not been exposed to much heat happened to be standing with their covering absolutely intact, while another column not far away in the same story of the building and evidently subjected to an intense heat had not only lost its covering, but had itself been practically destroyed by the fire. In no such case was I able to discover any evidence of earthquake damage in the covering that was intact, and there was nothing to indicate that one column might have had its covering damaged by the earthquake, while its neighbor escaped. More detailed information relative to fire damage is presented in the discussion of the individual buildings (pp. 76–108).

The earthquake did a great deal of damage, which could easily be differentiated from that due to the fire. As a rule brickwork in San Francisco was laid in lime mortar or in lime mortar gaged with a small amount of Portland cement. Wherever such masonry was subjected to serious earthquake shocks it was very badly shattered. Much of it came down in the ruins, and much of that which remained in place was reduced to a loose pile, without any adhesion between the mortar and the bricks. The bricks in general were more or less misplaced even where they did not come down, and many of them were broken. Where brickwork was solidly laid up in good Portland-cement mortar, if the earthquake shock induced stresses sufficient to damage it, the damage generally appeared in the form of well-defined cracks, which could have been easily pointed up, so as to leave the wall almost as good as it was before.

Well-executed stone masonry subjected to earthquake shocks showed, in many places, considerable slipping of the individual stones, the adhesion between the stones and the mortar having been destroyed. Here and there, where the strength of the mortar approached that of the stone, the stone itself was badly shattered and cracked. Where the wall ran in the direction in which the undulation seems to have been propagated, it generally showed an X-shaped crack (Pl. XXII, A), the legs of the X crossing the affected area in a diagonal direction. Where the masonry was very good these cracks were the only apparent damage, but where it was not so good the individual stones, bricks, or tiles, as the case might be, had been loosened from their beds and broken, so that the entire mass was shattered, although in many places still standing.

In steel-frame buildings put up in the ordinary way, without any special bracing, most of the earthquake effect was localized in piers between windows, as if a horizontal force had been applied to the floor above, tending to slide it with reference to the floor below. As this effect occurred in both directions, the piers referred to were generally marked with X-shaped cracks, and in addition the masonry was apt to be very much shattered. There seemed to be no general rule as to the place where this shattering effect occurred. In some buildings the piers in the one or two stories near the middle of the height of the building seemed to have suffered the most; in others, the piers nearer to the roof. One tall building, which extended far above its neighbors, was seriously damaged in practically every story above the neighboring buildings.

It was apparent that in some buildings the shock was so severe that probably no structure, however well built, could have withstood it absolutely without damage. It was equally apparent, however, that such great exhibitions of energy were confined to small areas, and that it would be possible to put up buildings in San Francisco which would come through a similar earthquake with very little damage except to individual buildings here and there.

Hollow-tile work seemed to be badly shattered by the earthquake in a great many places. Well-executed stone masonry, as a rule, stood better than brickwork. Brickwork built with good hard bricks, laid in Portland-cement mortar, stood better than that built with inferior bricks or inferior mortar.

Of all the structures which were manifestly exposed to severe shock the concrete buildings at Palo Alto stood best. It would seem to be a general rule that increased tensile strength, even in a brittle material, greatly increased the resistance to earthquake shock. The height above the ground at which the damage was greatest appeared to be largely a function of the distribution of mass in the structure itself, combined with the distribution of the bracing. If the base of a tall steel-frame building were subjected to a vibration tending to tilt it, manifestly some time would be required to set the upper part of the building in motion. As the vibration evidently occurred in both directions, there would be a reversal of motion before the upper part of the building had responded to the first impulse. Under these circumstances there would be established somewhere a center of oscillation, where very severe stresses, due to the acceleration of the superincumbent mass, would be largely concentrated.

It might have been supposed that most of the destructive effect of such action would be manifested at the joints in a steel-frame building; but around the joints are concentrated the ends of the floor beams and girders, together with the floor construction, and at the level of these joints is the only portion of the walls which is per-

fectly solid. The shafts of the columns at about midstory height are therefore less efficiently braced than the portions on a level with the floors. Moreover, it is probable that the play in the connections of the steel work at the floor level would permit a little motion here without any damage, provided, in the meantime, the bracing at midstory, due to the masonry, is sufficient to preserve the structure from collapse; thus the connections would escape without material damage. As a matter of fact, some such action seems to have taken place. There was very little damage at the points where the steel work was fastened together; at least, very little that was apparent.

The failure of the masonry in the piers seems to have prevented the columns from being broken across in the middle or permanently deflected. It is an interesting speculation how near some of the unbraced steel-frame buildings were to total collapse under the stresses above described. In my judgment many of them were a little too near for safety. I saw a number of field bolts or rivets that I thought had probably been sheared by the earthquake, but as to most of them I was not sure that they had ever been in place. In one or two instances, however, the earthquake effect was indisputable.

As it is very difficult to discuss the earthquake effect in a general way, however, it will be taken up further in connection with the subjoined detailed description of the effect of the earthquake and fire on individual buildings in San Francisco.

BEHAVIOR OF INDIVIDUAL STRUCTURES.

ACADEMY OF SCIENCES BUILDING.

The Academy of Sciences building, on Market street, was interesting because of its interior construction. This building had cast-iron concrete-filled columns and Ransome reenforced-concrete floor construction. So far as it was possible to ascertain, no damage was done to the reenforced concrete or to the columns by the earthquake. The building was gutted and the floors considerably damaged by the fire, but the columns were not damaged, and on the whole the building stood very well. A very good view of this building was given in the Engineering News of June 7, 1906, page 623. (See Pls. XXIV, *A*; XXV, *B*.)

ÆTNA (YOUNG, OR COMMISSARY) BUILDING.

The steel-frame structure at the corner of Spear and Market streets, locally known as the "commissary building," because it was said to have been erected originally with a view to furnishing offices for the Commissary Department of the Army, rests upon piles, and suffered relatively small damage from the earthquake. Pl.

XXV, *A*, shows the corner of the building and the subsidence of the street at this point. The inlet at the corner indicates the original level of the street. There was a vault under the Market street sidewalk, immediately behind the wall at the curb line. The basement floor in this vault was of concrete and had a total thickness of 7 or 8 inches. The earthquake caused the earth to bulge up in the portion of the basement under the sidewalk, rupturing the concrete floor and turning it up on its edge, so that where there had previously been a clear headroom of 7½ feet the highest point of the bulge was within 3½ feet of the beams carrying the sidewalk. The columns were of steel, protected with expanded metal and plaster. The girders were of steel and the space between them was spanned by reenforced-concrete construction. The reenforced-concrete beams were formed on the lower edge by a curved piece of flat steel (Pl. XXIX, *B*). The concrete floor construction was damaged by the heat to such an extent that a heavy load of sheet iron on the third floor broke through, though it did not fall through bodily. The expanded metal that was used for reenforcing the slabs from rib to rib evidently got hot and was ruptured at this point.

The cinder concrete used in the floor construction of this building was badly damaged by the heat, although the heat could not have been very intense, as otherwise the ribs, with their exposed metal reenforcement, must have failed. Moreover, the girders did not have their lower flanges protected, yet they remained straight. A great many of the ribs, however, were deflected very considerably, but, owing to the fact that they were curved to begin with, this deflection, due to the fire damage, was not very apparent. The columns themselves were practically uninjured, although the column covering was severely damaged, and will probably have to be totally renewed. There were some terra-cotta partitions, terra-cotta furring, and furred ceilings in this building, all of which totally failed. The brick wall at the west side of the building exhibited some earthquake cracks, and at a number of places the brickwork spalled under the heat.

APPRAISERS' WAREHOUSE.

The appraisers' warehouse was a very heavy structure, built on the old-fashioned monumental plan. (Pl. XXVIII, *A*.) It was entirely of brickwork, with some stone trimmings, and the exterior brickwork was laid with full header courses. It was practically undamaged by the earthquake, the chimney even being left standing, and the fire did not get into it. It is probable that the shock at the site of this building was not so severe as it was at some other places, or the chimneys, at any rate, would have been thrown down. The building itself shows a very few slight cracks, which may have been due to

ordinary settling and not at all to earthquake. Mr. Roberts, the local representative of the Supervising Architect's Office, informed me that during the construction of the building there had been some unequal settling, so that one end was about 1¼ inches lower than the other, but that this settling had been at a uniform rate from one end to the other, so that it had caused practically no damage. On the interior there were many solid brick partitions, with some unprotected cast-iron columns. The floor construction was of steel or iron beams and segmental brick arches with a span of 3 to 6 feet.

It is worthy of note that immediately after the earthquake and fire three of the very few buildings in the burned district which were absolutely open and ready for business in every particular were the post-office, the mint, and the appraisers' warehouse. The massive construction used in these Government buildings would appear to have been a very good investment.

ARONSON BUILDING.

The ordinary ten-story steel-frame structure at the corner of Third and Mission streets known as the Aronson Building had terra-cotta column coverings and partitions and cinder-concrete floors, all of which were of the types described in this paper as common in commercial buildings. The building seems to have been occupied for light commercial purposes, and the fire test to which it was subjected was therefore somewhat more severe than that prevailing in office buildings.

A column in the basement was buckled, and two of the columns on the first floor were badly buckled near the ceiling, as shown in Pl. XXVII, *B*. These results, so far as the condition of the fireproofing is concerned, are typical not only of the other stories of the Aronson Building, but of similar work in other buildings throughout the burned district. Some of the work in the Aronson Building was not severely tested by the fire and was still intact. An examination of it shows that it was as well done as similar work in any other commercial building in San Francisco. Where the fire was not very hot this kind of fireproofing protected the steel and suffered not more than 10 or 15 per cent of damage itself; where the fire reached the average temperature the fireproofing suffered a loss of 50 to 100 per cent, and where the fire was a little hotter than the average the total loss of the fireproofing and serious damage to the steel work was not at all uncommon. Damage to fireproofing such as that here described occurred in the James Flood Building, the Emporium Building, the building of the Spring Valley Water Company, the Mills Building, and every other building in which hollow tiles were used.

The buckled column in the basement was about the worst example of this sort of damage that I discovered, although I am inclined to

think that in one or two other buildings in which there was a general collapse of the steel superstructure worse columns than this one could have been found under the débris. The débris was not cleared away while I was in San Francisco, so I had no opportunity to see the condition of many columns that had evidently failed.

The basement of the Aronson Building was divided into several rooms by hollow-tile partitions. The room in which the buckled column was located had evidently contained an enormous amount of paper in some form or other, and the heat generated must have been very intense. The fire broke through the hollow-tile partition which separated this room from the adjacent one, but there was very little that was combustible in the latter, and the column standing there had its fireproof covering entirely intact. Examination showed that the work in this building was neither better nor worse than the average of similar work anywhere else in the San Francisco commercial buildings. A plain and inevitable inference is that wherever such work was practically undamaged the fire test was not at all severe.

In the same part of the basement as that in which the above-mentioned column was situated—that is, under the Third street wall of the building—there were two columns covered with cinder concrete. The concrete covering on one column made a very large and heavy pier; on the other it was about 4 inches thick. It was apparent that the heat in this front portion of the room was not quite as severe as it was farther back, where the buckled column was. Not only was there very much less evidence of fire in the way of ashes, etc., but the general indications pointed to a considerably lower temperature—although the heat at this point was very severe, nevertheless. The larger cinder-concrete pier was evidently damaged to some extent by the heat. The cement had apparently been dehydrated to a depth of one-fourth to three-eighths of an inch on the flat surface, and to a greater depth at the corners. The other pier showed more evidence of intense heat. It stood opposite the middle of the room, where there seems to have been the greatest accumulation of combustible matter. When I first saw this column the cinder concrete was dead and friable to a depth of nearly an inch. How much of this was due to original poor quality and how much to the action of the fire was difficult to determine, but fire damage was very evident. This pier showed on the surface a number of longitudinal cracks running from top to bottom, indicating that there had been a tendency for the concrete to fail and come off under the expansion stresses. At a later inspection a part of the concrete covering of this column had been knocked off, and it then became apparent that the cracks above referred to had extended entirely in to the surface of the column itself, and enough heat had got in to partly burn off the paint along the inner edges of the cracks.

The stairways in this building had apparently been partitioned off by hollow-tile partitions, but these were totally wrecked, and the stairways were in such condition that it was only with great difficulty and by going on all fours that they could be used to reach the upper story. In the west wall of this building I saw the remains of a wire-glass window, with metal sash and frame, which had been practically destroyed by the heat—probably, however, as a result of a simultaneous attack by the fire from both sides. Wire glass seems to have done some good service in other buildings in San Francisco, although in the Merchants' Exchange, as in the Aronson Building, it failed completely, so that a constructing engineer, who had drawn his conclusions entirely from what he saw in the Merchants' Exchange, was disposed to condemn wire glass outright.

BULLOCK & JONES BUILDING.

The steel-frame Bullock & Jones Building was faced with ornamental terra cotta, with hollow-tile column covering and reenforced-concrete slabs which were haunched on the beams, the slab reenforcement apparently not being continuous over the tops of the beams. Some of the floor slabs collapsed, and the column coverings failed entirely. Two columns in the third story had buckled in the same way the columns buckled in the Aronson Building. This building was rather more flimsy even than the average commercial building, and the fire nearly brought it down. Pl. XXVI, *A*, is an interior view showing the buckled columns in the second story. It will be observed that pipes were run up inside of the column coverings. Where similar conditions existed in Baltimore it was maintained by those interested in the particular system of column covering used that the pipes had got hot, expanded, and thrown the covering off. My own opinion was and is that the covering must have failed first, otherwise the pipe would not have become hot. It may be that after the covering had partially failed, the pipe got hot and completed the destruction, but if the covering had been efficient to begin with, there would have been no trouble with the pipe.

A comparison of the conditions in the Bullock & Jones Building with those shown in other views—for example, in the illustrations of the Aronson Building—is sufficient to justify the opinions herein expressed. Pl. XXVI, *A*, shows that one of the panels of the floor system had collapsed. My examination of the Bullock & Jones Building indicated that the reenforced-concrete floor construction was haunched on the lower flanges of the floor beams. The photograph confirms this observation, as will be seen by examining the naked floor beam which appears in the lower left-hand portion of the view. The reenforcement of a floor slab should always be con-

tinuous over the top of the beam; otherwise the construction is nothing but an arch, and develops the thrust to be expected of an arch. Moreover, as a rule, tie-rods are omitted when reenforced-concrete floor slabs are used, and it was naturally to be expected that reenforced-concrete floor slabs of this type would collapse to some extent; the wonder is that they did not collapse to a greater extent in the Bullock & Jones Building. The fire damage to ornamental terra cotta in this building was very conspicuous.

CALL BUILDING.

Of all the commercial buildings in San Francisco, by far the most interesting was that known as the Call (or Spreckels) Building, at the corner of Third and Market streets. This building is remarkable for the care and skill shown in the design of its steel work. It is a steel-frame building, all the walls, floors, partitions, etc., being carried on steel work. It has 15 main stories, in addition to the stories in the dome, or cupola, and rests upon a continuous foundation composed of concrete reenforced with steel beams. The building proper is about 75 feet square, but the foundation is about 90 by 110 feet, and was carried to a depth of about 25 feet below the sidewalk level. A fairly complete and satisfactory description of this building was published in the Engineering Record of April 9 and 16, 1898.

In the first four stories above the street the bents of the steel work adjacent to the four corners of the building on each side were braced with solid portal braces. In addition, eight interior bents were braced with diagonal tiebars from top to bottom. At all junctions of girders and beams with columns knee braces were used. The design of this steel work is well worthy of study by anyone interested in such structures. It is probably, on the whole, the best-designed piece of such work in the United States. Another remarkable thing about it is that the execution was apparently as good as the design. In a number of places where the fireproofing had come off the connections were exposed, and the workmanship here seemed to have been practically as good as it could well be made. I particularly noticed the column bearings, and they seemed to be absolutely close and true. Inaccurate column bearings in building work are so often seen that one is almost justified in saying that they are the rule rather than the exception; but in the Call Building such connections as were exposed to view had been put together with extreme accuracy.

The column covering in this building was of hollow tiles, about 3 inches thick, with very thin webs. Partitions were built of the same material. The floor construction was of reenforced cinder concrete. Some furred ceilings composed of wire lathing and light furring strips were also used. The outer walls were furred with 2-inch

hollow tiles. When I saw the building the column coverings and partitions throughout were either down or so badly shattered that nearly all of them would have to be taken down and rebuilt, and the furring had fallen from many of the outer walls. The chief engineer of the building stated that it was practically undamaged immediately after the earthquake, and that the fire which subsequently gained access did not damage it very much, but that a large part of the ruin of the partitions and column coverings was due to the concussions from the dynamite used in demolishing dangerous walls in the neighborhood.

The hollow-tile covering of the steel work came down pretty generally throughout the building. Whether or not this failure resulted from the fire, close examination of the steel work proved that the tile covering was totally inadequate, because in many places there had been heat enough to burn the paint entirely off the steel and to leave indications of high temperature on the metal itself. Photographs taken of the Call Building during the progress of the fire indicate that the fire was not very fierce, yet, in my judgment, some of the steel members were very close to serious damage as a result of it. So magnificent a piece of steel work deserved better fireproof covering than it had; but, as a matter of fact, the steel itself was observed to be fire blackened in many places. The furred ceilings in this building in general suffered so much damage that they should be taken down altogether. The marble finish throughout, while not absolutely destroyed, was so damaged as to be worthless. The reenforced-concrete floor slabs stood fairly well, but some of the concrete looked as if it had suffered appreciably from the heat.

On the exterior the Call Building showed absolutely no damage from the earthquake except in the story immediately above the main cornice, where, in the parts adjacent to the four corners, a few stones had evidently slipped so that the joints had opened up for possibly half an inch or more. The exterior of the building was faced with the grayish-green sandstone which is used for so many buildings in San Francisco. This stone, wherever the fire struck it, not only spalled very badly, but had its color very largely burned out, so that what remained was a dull and lifeless buff gray, the green having totally disappeared.

Examination of the Call Building from the exterior produced the impression that it was slightly out of plumb to the southeast, but later information showed that this estimate of the direction in which the building leaned was incorrect. Captain Kelly kindly sent a man with a plumb line to verify the observation. He plumbed the building from the tenth floor, as its dimensions were reduced somewhat above this point. He found that the building leans uniformly toward Market and Third streets; at the tenth floor the building overhangs

Market street by 8 inches and Third street by 10 inches. This indicates clearly that it is not safe to trust the eye in the matter of a building out of plumb, because when previously examined—not only once but several times—the Call Building presented the appearance of leaning away from Market street instead of toward it. In my judgment the deviation from the vertical in this building may have been due in whole or in part to the earthquake, but it is not at all impossible that it may have been built out of plumb. With the rigid type of connections used in the Call Building, strict mathematical accuracy of construction at all points would be essential to insure the exact perpendicularity of the building. As this accuracy is practically unattainable, it is ordinarily necessary to accept slight deviations from the plumb line and probably, in the majority of cases, a certain amount of torsion in the frame itself. So far as these deviations are kept within reasonable limits they make no serious difference, and the building is just as good for all practical purposes as if it were perfectly plumb and true.

On the whole, the foundations and steel frame of this building were admirably designed. The bracing of the steel work seems to have taken up the vibration due to the earthquake, so as to preserve the masonry of the outer walls. As long as there is no deflection sufficient to crack the masonry, there can be no doubt that the building is safe. It is a question whether other buildings which were not so well braced, and in which the piers between windows were badly shattered, were not dangerously near collapse, and it may well be doubted whether there is not serious damage to the steel work as it is. This matter could be determined only by uncovering the steel and making a detailed inspection.

The only safe plan in the construction of steel-frame buildings is the one followed in the Call Building—that is, to brace the steel work so that by itself it is able to resist the stresses due to the vibration. The engineer who designed the foundations and steel frame of this building may well be gratified at the admirable manner in which his structure fulfilled its purpose. Had the building been as well designed to resist fire as to resist earthquake, it is probable that the total damage would have been very much less than it was.

CHRONICLE BUILDINGS (OLD AND NEW).

The old Chronicle Building (Pl. XXX, *B*) seems to have been built in two parts—a west and an east wing. The west wing had protected cast-iron columns, rolled beams, and terra-cotta fireproofing. The interior structure had entirely collapsed, apparently from the heat. It was impossible, with the débris piled around it, to determine just what the cause of the failure was, but it was probably

due to the buckling or rupture of a lower-story column by the fire. In the east wing of the old building the terra-cotta fireproofing had suffered, to a considerable extent, the typical damage which is described in connection with the Aronson Building (p. 78) and in the general discussion of the subject (p. 72). Many floor tiles had lost their lower webs.

The new Chronicle Building (also shown in Pl. XXX, *B*) was badly racked by the earthquake from the point where it rose above the neighboring buildings to the top. It seems to have been provided with knee braces tending to stiffen it in a direction parallel to the Kearney street front. In the first story, at any rate, there were some diagonal braces in the steel work of the north wall. The worst damage was to the masonry of the Kearney street front; the shattering of this masonry can be observed by a close inspection of Pl. XXX, *B*. This building was unfinished. It had hollow-tile fireproofing, including partitions. The burning out of the window trim and of whatever combustible matter may have been in the building, caused a good deal of damage to the hollow-tile floors, especially near the windows, where the lower webs came off almost completely.

The old Chronicle Building seems to have suffered very little from the earthquake, notwithstanding it must have acted as a buttress for the new building.

CITY HALL AND HALL OF RECORDS.

The new city hall in San Francisco (Pl. XXXI), together with the hall of records, which adjoins it and which formed practically a part of one and the same structure, was a massive brick building with steel floor beams. This building had corrugated-iron floor arches, leveled up with concrete. There were some naked cast-iron columns where the span from wall to wall was too great for the beams. All interior partitions of any importance were of brick and rather heavy. In the basement and subbasement the corrugated-iron arches were left exposed. Everywhere else there was a ceiling carried on a form of metal lathing consisting of sheets of metal crimped so as to form dovetailed grooves or ribs; the plaster, being pressed up against this lathing and into the dovetailed grooves, was enabled to hold on by the key thus formed. The girders in the building were protected by a wrapping of this metal lathing finished on the exterior with plaster. The brickwork in the city hall was made of a very good quality of common bricks. The mortar appeared to be lime mortar gaged with cement, and was distinctly superior to lime mortar pure and simple. The workmanship was also above the average. The bricks were not as well laid as they might be, yet it was not poor

work by any means. I found a few places where joints were not well filled, but not a greater number of such places than one would expect to find even in fairly good work. On the exterior the building was finished with stucco, which was tinted to imitate the grayish-green sandstone so much used for building purposes in San Francisco.

The city hall was of an irregular plan, as it was built on a triangular lot. The building contained in the western part an interior court, in which a nonfireproof structure had been erected prior to the earthquake and fire to accommodate the fire-alarm headquarters. On the southeast front of the building a little to the east of the center was a rotunda with a tower and dome above it. This tower was built of brickwork up to the base of the upper of two peristyles of free pillars around the outside of the tower. This peristyle was composed of steel columns covered with hollow tiles, so as to form a pillar of circular section with an entasis. The walls of the tower from the base of this peristyle up also seem to have been of hollow tiles. At the base of the dome was a floor composed of terra-cotta flat arches. It was reported that the masonry of the building had been reenforced to a great extent with embedded steel bars for the purpose of increasing its resistance to earthquake. I did not notice any such bars myself, but it was very difficult to get such access to the débris as would have permitted the verification of this point.

In a general way it may be said that the southwest half of the building was practically destroyed by the earthquake. The heavy masonry was thrown down, so that the entire southwest half of the tower was left entirely exposed, the dome standing on the steel work alone. The remaining half of the building showed considerable damage from the earthquake, but the principal damage here was due to the fire. Pl. XXXI gives a fair idea of the earthquake damage in the southwest half of the building.

It will be observed that some of the projecting pilasters on the exterior of the wall were badly cracked. A singular action of the earthquake, as exhibited here and in other places, was the tendency to shear off projecting pilasters even though they were built of the same material as the wall and well bonded to it. In my judgment this action was due to the fact that the earthquake caused the wall to rock slightly sidewise. When it rocked toward the side from which the pilasters projected, the entire weight would be for an instant concentrated on the base of the pilaster in such a way as to tend to shear it loose from the wall, which actually happened in many cases, the wall presenting no other evidence of damage whatsoever. Instances of this damage are pointed out in the discussion of other buildings.

Examination of Pl. XXXI, especially with a reading glass, will show that many of the diagonal braces in the steel work of the tower

quality and the arches were very heavy. Many of the floor beams were 24 inches deep, and that was consequently the depth of concrete at the haunches. The thickness at the crown seems to have been not less than 5 or 6 inches, and the span between floor beams was not more than 6 or 7 feet. A concrete arch of such dimensions and such span, even though it had been made of very poor concrete, should have stood perfectly well had it been depending on its own power of resistance alone. In a number of places where the floor did not collapse the effect of heat on the exposed lower flanges of the 24-inch beams was sufficient to produce a deflection of 6 or 7 inches on a span of 25 or 30 feet. This result indicates clearly the necessity of protecting the exposed flanges of all beams.

Pl. XXVI, *B*, shows some unconsumed papers about the base of the cast-iron column. These papers came from a vault which opened into this room and the contents of which were charred, but not destroyed; all the combustible contents of the room proper were destroyed. The dark splotches on the wall in the background are due to spalling of the brickwork at the surface under the influence of the fire. This phenomenon was noticed in a number of places in San Francisco, just as it was in Baltimore; but as a rule the spalling did not penetrate to a greater depth than half an inch, and the wall itself was practically as good as before. In the fire at San Francisco, as in every other large fire, the right kind of brickwork proved to be more resistant than any other material.

A good deal of the plaster on the interior walls in the city hall was on wooden furring studs and wooden laths. Why this kind of work should have been done is beyond comprehension. Many of the corridors would have suffered practically no damage but for this one circumstance. As the fire burned out the wooden trim of openings between the corridors and the rooms it gained access to the wooden furring and burned it out behind the plaster, thereby bringing most of the plaster down. There were, however, many square yards still standing, although the wooden furring studs and laths had been burned out behind. There would appear to have been no reason for furring these interior walls; the plaster could just as well have been applied to the brickwork itself. As a matter of fact, in many parts of the building it was so applied, though in other parts the walls were furred with metal lathing and studs. Why a uniform treatment wa not adopted is not apparent.

The halls of the building were generally floored with marble tile. Ex- The heat had apparently not been very intense these tile and came up, and the marble was rendered chalky, was completely ruined.

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templates that were subjected to the heat were badly spalled and shattered, and one or two of them had failed sufficiently to permit the ends of the girders to settle an inch or more. I also noticed a number of places in the walls of the building where the fire had evidently found its way into the interior of unfilled joints through very small and tortuous passages.

The hall of records was connected with the city hall by means of an arcaded corridor. The building was circular and all the floors above the first were pierced so that they practically formed galleries. The beams supporting these upper floors or galleries were of steel, set radially and supported at their inner ends by girders carried on a peristyle of 12 circular cast-iron columns, which had no fireproof covering of any sort. The floor arches were segmental arches of common bricks. The lower flanges of the beams were exposed, but the evidence indicated that there must have been a suspended ceiling of some sort below the fireproof floor construction, although it was impossible to determine its nature. It is probable that it was carried on combustible supports of some kind, which have totally disappeared. As the records had been carried away from this building before the fire reached it the heat within it was not very intense and the interior of the structure was standing in a comparatively undamaged condition, except for finish. The exterior walls, however, were badly shattered by the earthquake. The window shutters were of iron, and if they had remained in place, considering the situation of this building, would probably have kept the fire out. As indicated in the view, however, the earthquake wrenched some of these shutters, with their surrounding masonry, entirely out of the wall, thereby, of course, leaving easy access for the flames.

As previously stated, it is my opinion that to remove the débris and restore the city hall, including the hall of records, to its original condition would cost as much as the entire building cost in the beginning. As it was so badly damaged by the shock it would apparently be wise to remove it altogether and build a structure of another type designed to resist earthquakes.

COWELL BUILDING.

No special interest attaches to the Cowell Building, except that it seems to have been more flimsy than the average. It had unprotected steel work and girders and wooden-joisted floors. The effect of fire on the unprotected steel work is well illustrated in Pl. LI, *B*.

CROCKER BUILDING.

The Crocker Building had a steel frame and hollow-tile fireproofing. Some of the tile arches had totally collapsed, and over large

quality and the arches were very heavy. Many of the floor beams were 24 inches deep, and that was consequently the depth of concrete at the haunches. The thickness at the crown seems to have been not less than 5 or 6 inches, and the span between floor beams was not more than 6 or 7 feet. A concrete arch of such dimensions and such span, even though it had been made of very poor concrete, should have stood perfectly well had it been depending on its own power of resistance alone. In a number of places where the floor did not collapse the effect of heat on the exposed lower flanges of the 24-inch beams was sufficient to produce a deflection of 6 or 7 inches on a span of 25 or 30 feet. This result indicates clearly the necessity of protecting the exposed flanges of all beams.

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The halls of the building were generally floored with marble tile. Even where the heat had apparently not been very intense these tile floors expanded and came up, and the marble was rendered chalky, while the color was completely ruined.

In this building a number of girders or lintels rested upon stone templates, which were exposed at the face of the wall. All such

templates that were subjected to the heat were badly spalled and shattered, and one or two of them had failed sufficiently to permit the ends of the girders to settle an inch or more. I also noticed a number of places in the walls of the building where the fire had evidently found its way into the interior of unfilled joints through very small and tortuous passages.

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COWELL BUILDING.

No special interest attaches to the Cowell Building, except that it seems to have been more flimsy than the average. It had unprotected steel work and girders and wooden-joisted floors. The effect of fire on the unprotected steel work is well illustrated in Pl. LI, *B*.

CROCKER BUILDING.

The Crocker Building had a steel frame and hollow-tile fireproofing. Some of the tile arches had totally collapsed, and over large

areas—probably at least 30 per cent of the whole—they had lost their lower webs. There was nothing of special interest in this building more than has been described with other buildings. The damage seemed to be about as great as the average—probably more than 60 per cent.

CROCKER ESTATE BUILDING.

Pl. XXVIII, *B*, shows the kind of damage to ornamental terra cotta which is typical of both earthquake and fire action. This particular view was selected because it was possible to take it from a point near by so as to show the damage in detail. The Crocker Estate Building, a part of which is shown in the view, had cinder-concrete floor slabs, rolled beams and girders, and naked cast-iron columns. The fire was evidently not very hot in this building. The lower flanges of the beams and girders were covered with expanded metal and plaster. The webs of the beams were protected with cinder concrete built out solid from the webs to the edge of the flange. The rear portion of this building and a building of similar construction on the east had largely collapsed, apparently as a result of the action of the fire on the naked cast-iron columns. At this and every other point where exposed cast-iron columns had failed it was often noticed that the heads of the columns broke off and remained attached to girders and beams by means of the lugs and bolts. This result confirms conclusions derived from certain experiments made a number of years ago, to the effect that the lugs, ribs, etc., at the heads of cast-iron columns are the source of severe shrinkage stresses, with consequent weakness in the column.

DEWEY MONUMENT.

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reported that this building was dynamited three times during the progress of the fire, although I was assured by a policeman, who claimed to have been on duty during the whole time, that this report was not true. Under the circumstances, it is a little difficult to draw a reliable conclusion from the state of affairs in the Emporium. However, examination of the ruins indicated very strongly that much of the trouble was due to the inadequacy of the fireproof protection to the steel work.

Pl. XXXII, *A*, is a general view of the collapsed portion of the building and illustrates the failure of the terra-cotta column covering in various stages. The hollow-tile end-construction arches in the mezzanine floor had collapsed over considerable areas, under the influence of heat alone, as the evidence plainly indicated that nothing could have been precipitated upon them and that they were not subjected to an explosion. A considerable portion of the rear wall of the Emporium, which had been thrown down, probably partly by earthquake and partly by the fire, presented one case of very excellent mortar used in a commercial building. The mortar was better than the bricks, and both were of good quality. The fireproofing in the lower part of the building was quite as good as that ordinarily found in similar structures throughout the country. In fact, it would be easy to point out department stores not so well fireproofed as the lower part of the Emporium.

I have always been of the opinion that the Horne store in Pittsburg, which was the first large fireproof department store to be tested by fire, was really closer to collapse from the heat than is generally believed. After the covering has been stripped from a steel column, the time and heat required to bring it down are not very great. The fact that the covering comes off during a fire is absolute proof that it is wholly inadequate. If the steel column stands up, notwithstanding the loss of its covering, it is due to good luck and not at all to good fireproofing. In the Horne store the covering was stripped from a number of columns; in the Emporium Building the same thing happened, but the heat continued a little longer, and there is no doubt in my mind, after an examination of the ruins, that at least a portion of the collapse was due to the failure of the columns under heat. The floor tiles in the Emporium Building lost their lower webs in large quantities, where the arches themselves did not collapse; and tiles in the column covering which did not come off bodily also lost their exposed webs in considerable quantities. The ruins of the Emporium were in a very dangerous condition, so that a detailed inspection was not practicable; and it is doubtful whether any useful results would have followed, because the fireproofing was of the ordinary commercial type which has often enough been proved inadequate to resist a serious fire.

FAIRMOUNT HOTEL.

The lower two stories of the Fairmount Hotel (Pl. XXXIV) were of concrete. The next story, the first, was built of granite, apparently backed with brickwork, and above that the building was faced with ornamental terra cotta. The earthquake damage to this terra cotta was severe. Neither the granite nor the concrete walls of this building seemed to have suffered materially from the earthquake, but the granite was badly damaged by the fire. The building was surrounded by a wide open space, and the fire must have been very fierce in its vicinity to have ignited it. I was informed that considerable damage was done to the steel work and fireproofing in this building; but as the owners, or at least those in charge, objected to having it inspected, and as it was an unfinished building, I made no examination of its interior. If, under the circumstances, it suffered seriously from the fire, the only conclusion that could have been drawn was that the fireproofing was very poorly done.

JAMES FLOOD BUILDING.

The new James Flood office building, situated on the north side of Market street, opposite the Emporium Building, had a steel frame, segmental hollow-tile floor arches, terra-cotta column covering and partitions, and furred ceilings of metal lath and plaster. The hollow-tile column covering and partitions failed in this building in the same manner as in others, and to about the same extent as in the average building. The lower stories seem to have been occupied for mercantile purposes, and here the fire damage was greater than it was above. Pl. XXXV, *A*, is a view taken in the first story of the Market street wing. The second and third columns from the front are slightly buckled to the right. They were covered with hollow tiles in about the same way as the columns shown in the Aronson Building. The columns in the James Flood Building were Z-bar columns and were filled in solidly with brickwork, in addition to the hollow-tile covering shown in the view. In my judgment, this construction was the only thing that saved the Market street wing of this building from collapse, because there was every evidence that the columns which were found slightly buckled had reached a dangerous temperature, and would probably have come down and wrecked all of the building above them had it not been for the stiffening effect of the brick filling.

Pl. XXXIII, *B*, shows a doorway in the west front of the James Flood Building illustrating the damage by earthquake to the sandstone piers. The stone used in this building was the same grayish-green sandstone that is described in connection with other buildings,

and at each principal entrance there was a groined-arch ceiling made of it. These ceilings were so badly cracked and damaged that they will probably have to be taken down and rebuilt.

GRANT BUILDING.

The structure at Seventh and Market streets known as the Grant Building illustrated the capricious variation in intensity of the earthquake shock within short distances. This building was separated from the post-office by a very narrow street, hardly wider than an alley. The building had cinder-concrete floor slabs, furred ceilings in the upper stories, and terra-cotta partitions. Although it was a commercial building of very ordinary type, it was only slightly damaged by the earthquake, but was gutted by fire. It was entirely outside the area of surface disturbance, the streets in its vicinity showing no signs of settlement or upheaval. The fire was not very hot apparently, but was just about able to take the plaster off the under part of the floor construction without seriously damaging the latter. The terra-cotta partitions were all down. There was no evidence of superiority of construction, however, as everything pointed to moderate tests by both earthquake and fire.

HALL OF JUSTICE.

The Hall of Justice was one of the municipal buildings which was seriously damaged by the earthquake. A general view is shown in Pl. XXXIX, *A*, but does not bring out the damage that really occurred. In the basement of this building was another example of buckled columns. The columns were covered with expanded metal and plaster. This covering failed at a point near the floor, and the columns buckled and sank, producing the same effect as if they had been punched into the ground. The column coverings throughout this building failed very generally from the fire.

KAMM BUILDING.

The Kamm Building was situated on Market street, west of the Call Building. The rear portion was extended eastward by a short ell, so that it was wider than the front. It was occupied in the first story and basement by a wall-paper establishment. The columns were protected by metal lathing and plaster.

The burning of the wall paper in the basement caused general buckling of the basement columns to such an extent as to result in the collapse of all the interior framework of practically the entire rear portion of the building. A good view of this building is to be found in the Engineering Record of May 26, 1906, on page 645.

KOHL BUILDING.

The Kohl Building was of steel-frame construction faced with the grayish-green sandstone which is referred to so often. It had reenforced-concrete floors with furred ceilings and partitions of metal lath and plaster. The window frames and sash were metal covered, and there was very little combustible matter in the finish. The doors, with their frames and jambs, were of wood covered with sheet metal. It is manifest that this building was not subjected to very intense heat, as the windows above the fourth story were unbroken and the stone was comparatively undamaged. The first, second, and third stories were burned out, and there was some damage in both the fourth story and the attic.

The metal-covered doors in this building, however, prevented to some extent the spread of the fire within the building itself, so that where one room burned out, the fire coming in through a front window, an adjacent room was not burned because of the resistance offered by the door. The building could hardly have been subjected to a very fierce heat, however, for, if it had been, the light partitions would have failed, in which case the metal-covered doors would have been of no avail. Where the heat was really intense, the wood of doors, frames, and windows burned out under the metal anyway, but of course the metal covering delayed the ignition of the wood and later prevented it from burning freely.

MERCHANTS' EXCHANGE BUILDING.

The structure known as the Merchants' Exchange was a steel-frame building with Roebling cinder-concrete flat floor slabs, double wire-lath and plaster protection for the columns, and partitions made of light furring irons, wire lath, and plaster. In some places wire lath and plaster were applied to both sides of the furring strips; in others the furring strips with the wire lath were simply plastered on both sides. This was one of the buildings in which the vault walls were made of the same materials as the partitions. Every vault in the building failed. All the partitions in the building were a total loss; not only did the plaster have to come off, but the metal framework had to come down also. The floor construction had a furred ceiling below it. The plaster had come down because of the heat on nearly all the ceilings, and probably as much as 20 per cent of the furring rods and wire lathing were down.

Large areas of the face bricks were shaken from the wall of this building, owing to the fact that they were laid without bond. The rear wall was also damaged by the earthquake. The adhesion of the bricks and mortar seemed to be largely destroyed throughout the wall,

without, however, producing any very large cracks. It is doubtful whether the wall is really safe in its present condition. On the inside of this building some of the wall columns were covered with 4 inches of brickwork projecting from the inner face of the wall as a pilaster. Some of these brick coverings had cracked almost entirely away from the main walls, besides being cracked vertically at other points in a manner similar to the cinder-concrete column coverings in the basement of the Aronson Building described on page 79. The brickwork in these places seemed to have been rather below the average in quality. It is not entirely certain whether the fire or the earthquake caused the cracks, but all the columns seem to have been uninjured, although the brickwork of one or two was so badly damaged that it ought to be taken down and rebuilt. Some enameled bricks were practically ruined by the fire, which stripped off the enamel face (Pl. XL, *A*).

MILLS BUILDING.

The large steel-frame Mills Building was without special bracing. The floors were of hollow tiles on the end-construction system, and the remainder of the fireproofing was likewise of hollow tiles. The tile arches lost their lower webs to a great extent, and some of them collapsed, apparently from heat alone; the column coverings failed very generally, and the girder coverings to a somewhat less extent (Pl. XLV, *B*). One basement column buckled under the action of the heat (Pl. XL, *B*). The conditions in the Mills Building as to column coverings and partitions were similar to those in the Aronson Building.

UNITED STATES MINT.

The mint was an old-fashioned monumental structure with granite walls and segmental brick-arch floor construction, carried on iron beams. A general view, showing the southwest front, is presented in Pl. XXXVIII, *A*. The building seems to have been practically uninjured by the earthquake, the only damage visible being at the base of the right-hand brick stack. It is probable that the shock at the locality of the mint was not so severe as it was at the new post-office building, although the two are only a few blocks apart; yet the result may be an indication that the solid old-fashioned monumental walls with the stonework solidly backed up by brickwork constitute after all one of the best types for resisting earthquake shocks.

It is somewhat surprising that the brick stacks were not overthrown, but I am informed that the thickness of the masonry in these stacks was very great, which probably explains their stability. The northwest (Pl. XXXVIII, *B*) and northeast faces of the mint were

considerably damaged by the fire, but the fire was kept out of the building proper by means of water from an artesian well equipped with fire pumps, located in the building.

MONADNOCK BUILDING.

The structure known as the Monadnock Building was an ordinary steel-frame office building, which was in process of erection. It was badly racked by the earthquake. Every one of the piers in which the earthquake cracks appeared was so badly shattered that no repairs short of tearing down and rebuilding would suffice. As a matter of fact, it is probable that adequate repairs to the masonry in the front wall of this building would involve reconstructing more than half of it. It would appear that there must have been rather severe vibration to shatter the brickwork so badly. Whether the steel escaped injury is a question of considerable interest, which can not be settled until the masonry covering is taken off.

MUTUAL LIFE BUILDING.

The Mutual Life Building was a steel-frame structure of the same general type as the Mills Building, and it suffered in the same general way, though possibly not quite so much. Some of the floor arches had collapsed, apparently from falling weights of some sort. (See Pl. XLII, *A*.)

PACIFIC STATES TELEPHONE AND TELEGRAPH BUILDING.

The Pacific States Telephone and Telegraph Building, on Bush street, illustrated the tendency of the earthquake to shear off projecting pilasters (Pl. XLI, *A*). This building had a steel frame, stone-concrete floor arches, furred ceilings above the basement, and concrete column and girder coverings. The front windows were of plate glass in metal-covered sash, with rolling steel shutters on the outside. The side and rear windows were of wire glass in metal-covered sash and frames, with sliding tin-covered wooden shutters on the inside.

The window protection seems to have prevented the entrance of fire from the outside, but in some other way an interior fire was started which completely gutted the building. The interior fire practically destroyed the plate glass, but not the rolling steel shutters. It seriously damaged the tin-clad shutters, but did not damage the wire glass appreciably. Had the interior fireproofing been as efficient as the window protection it is doubtful whether this building would have been burned out, for the interior fire should have been confined to the place of its origin. For these probable facts as to the

history of the fire in this building I am indebted to S. A. Reed, consulting engineer for the committee of twenty of the National Board of Fire Underwriters. Mr. Reed states, however, that the history of the fire here must be largely surmise, because reliable evidence was not obtainable.

This company had also a building with reenforced-concrete floor construction and wire-glass protection for its windows for one of its branch exchanges. The exposure of this building was probably not very severe. It was three stories high and the fire got into the upper story and cleaned it out; but the floor construction prevented the fire from extending into the stories below, which suffered practically no damage to structure or contents. A part of the third-story wall was thrown down either by the earthquake or by some other means, and this damage may have opened a way for the entrance of the fire.

PALACE HOTEL.

All of the interior and the exterior walls of the Palace Hotel, on the south side of Market street, were built of brickwork. It is reported that the brickwork was reenforced with embedded iron bars. The structure stood remarkably well, and there is little indication of earthquake damage. The building was nonfireproof, and was, of course, completely burned out, but the walls still stand almost as good as ever. (See Pl. XXX, *B*.)

POST-OFFICE BUILDING.

The steel-frame and granite post-office building (Pls. XLII, *B*; XLIII; XLIV) was carried on isolated grillage foundations, each column having its own footing. The diagonals of the building ran nearly north and south and east and west, the south corner being at Seventh and Mission streets. To the south and west of Mission street was an elongated, narrow, curved area in which the earthquake damage was very severe. It was commonly reported that this area, which was not far from the south corner of the post-office building, was a stream bed or ravine that had been filled within the recollection of the older inhabitants of San Francisco. Through the courtesy of J. W. Roberts, the local representative of the Supervising Architect's Office of the Treasury Department, I was enabled to make a detailed inspection of the building, and he also gave me very complete information as to the history of the building and the causes of the various items of damage which were in evidence at the time of my inspection. Mr. Roberts, who is evidently a cool and accurate observer, seemed of the opinion that the material under the building was a natural deposit, and not an artificial fill. But toward

quality and the arches were very heavy. Many of the floor beams were 24 inches deep, and that was consequently the depth of concrete at the haunches. The thickness at the crown seems to have been not less than 5 or 6 inches, and the span between floor beams was not more than 6 or 7 feet. A concrete arch of such dimensions and such span, even though it had been made of very poor concrete, should have stood perfectly well had it been depending on its own power of resistance alone. In a number of places where the floor did not collapse the effect of heat on the exposed lower flanges of the 24-inch beams was sufficient to produce a deflection of 6 or 7 inches on a span of 25 or 30 feet. This result indicates clearly the necessity of protecting the exposed flanges of all beams.

Pl. XXVI, *B*, shows some unconsumed papers about the base of the cast-iron column. These papers came from a vault which opened into this room and the contents of which were charred, but not destroyed; all the combustible contents of the room proper were destroyed. The dark splotches on the wall in the background are due to spalling of the brickwork at the surface under the influence of the fire. This phenomenon was noticed in a number of places in San Francisco, just as it was in Baltimore; but as a rule the spalling did not penetrate to a greater depth than half an inch, and the wall itself was practically as good as before. In the fire at San Francisco, as in every other large fire, the right kind of brickwork proved to be more resistant than any other material.

A good deal of the plaster on the interior walls in the city hall was on wooden furring studs and wooden laths. Why this kind of work should have been done is beyond comprehension. Many of the corridors would have suffered practically no damage but for this one circumstance. As the fire burned out the wooden trim of openings between the corridors and the rooms it gained access to the wooden furring and burned it out behind the plaster, thereby bringing most of the plaster down. There were, however, many square yards still standing, although the wooden furring studs and laths had been burned out behind. There would appear to have been no reason for furring these interior walls; the plaster could just as well have been applied to the brickwork itself. As a matter of fact, in many parts of the building it was so applied, though in other parts the walls were furred with metal lathing and studs. Why a uniform treatment was not adopted is not apparent.

The halls of the building were generally floored with marble tile. Even where the heat had apparently not been very intense these tile floors expanded and came up, and the marble was rendered chalky, while the color was completely ruined.

In this building a number of girders or lintels rested upon stone templates, which were exposed at the face of the wall. All such

templates that were subjected to the heat were badly spalled and shattered, and one or two of them had failed sufficiently to permit the ends of the girders to settle an inch or more. I also noticed a number of places in the walls of the building where the fire had evidently found its way into the interior of unfilled joints through very small and tortuous passages.

The hall of records was connected with the city hall by means of an arcaded corridor. The building was circular and all the floors above the first were pierced so that they practically formed galleries. The beams supporting these upper floors or galleries were of steel, set radially and supported at their inner ends by girders carried on a peristyle of 12 circular cast-iron columns, which had no fireproof covering of any sort. The floor arches were segmental arches of common bricks. The lower flanges of the beams were exposed, but the evidence indicated that there must have been a suspended ceiling of some sort below the fireproof floor construction, although it was impossible to determine its nature. It is probable that it was carried on combustible supports of some kind, which have totally disappeared. As the records had been carried away from this building before the fire reached it the heat within it was not very intense and the interior of the structure was standing in a comparatively undamaged condition, except for finish. The exterior walls, however, were badly shattered by the earthquake. The window shutters were of iron, and if they had remained in place, considering the situation of this building, would probably have kept the fire out. As indicated in the view, however, the earthquake wrenched some of these shutters, with their surrounding masonry, entirely out of the wall, thereby, of course, leaving easy access for the flames.

As previously stated, it is my opinion that to remove the débris and restore the city hall, including the hall of records, to its original condition would cost as much as the entire building cost in the beginning. As it was so badly damaged by the shock it would apparently be wise to remove it altogether and build a structure of another type designed to resist earthquakes.

COWELL BUILDING.

No special interest attaches to the Cowell Building, except that it seems to have been more flimsy than the average. It had unprotected steel work and girders and wooden-joisted floors. The effect of fire on the unprotected steel work is well illustrated in Pl. LI, *B*.

CROCKER BUILDING.

The Crocker Building had a steel frame and hollow-tile fireproofing. Some of the tile arches had totally collapsed, and over large

areas—probably at least 30 per cent of the whole—they had lost their lower webs. There was nothing of special interest in this building more than has been described with other buildings. The damage seemed to be about as great as the average—probably more than 60 per cent.

CROCKER ESTATE BUILDING.

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had apparently been covered in by a furred beam, or other architectural feature, since destroyed, was entirely devoid of protective covering. A great many people in San Francisco regarded the behavior of these columns as a substantial recommendation of cinder concrete, but the whole building bears evidence of having been subjected to only a moderate heat.

SHREVE BUILDING.

The columns in the first and second stories of the Shreve Building were covered with cinder concrete; those in the upper stories with hollow tiles. All the evidence in this building points to a moderate heat. The plastering on the columns was not seriously damaged, and such plastering never stands an intense heat. The hollow tiles on the columns came off very generally, but it is probable that the heat was more intense in the upper portion of the building than in the lower portion. This theory is supported by the fact that the damage to the masonry adjacent to the windows was most severe in the upper stories.

This building, like the St. Francis Hotel, is cited as an example of the excellent behavior of cinder concrete as a column covering, but in this case also there is every reason to believe that the concrete did not receive a severe test. The only cinder-concrete covering I saw that had evidently received an extreme test was in the basement of the Aronson Building, as described on page 79.

SLOANE BUILDING.

The mercantile structure known as the Sloane Building, at 114 Post street, had cast-iron columns, protected with expanded metal and plaster. The floor slabs were of expanded metal and cinder concrete. The basement of this building was subjected to an extremely fierce heat. At least six or eight of the columns had their covering destroyed, and the columns themselves either buckled or failed to such an extent that a large portion of the framework above was knocked down afterwards as a matter of safety. In the rear of the basement two rows of columns across the entire width of the building had practically all failed in the same way, but the débris was piled around them to such an extent that views could not be obtained.

SPRING VALLEY WATER COMPANY'S BUILDING.

The Spring Valley Water Company's Building, at Post and Geary streets, was used for office purposes in the upper stories and for mercantile purposes in the first and second stories. The southeast corner had totally collapsed (Pl. L, A), apparently from the failure of the

basement or first-story columns under the action of the heat. Pl. XLV, *A*, is a view taken in the first story of this building, which had been occupied by the City of Paris Dry Goods Company. This view is submitted as illustrating a typical but rather bad example of the loss of lower webs from hollow-tile floor arches. The column coverings shown in the view had suffered about as little as any others. The coverings of other columns in the same building were practically destroyed, as were also the partitions. The same sort of damage as that shown in Pl. XLV, *A*, was plainly visible in some of the upper stories of this building, especially the second story.

A stairway carried on unprotected cast-iron strings was destroyed by the heat in this building. The same thing occurred in a number of other buildings in San Francisco, even where the stairways had been walled off by hollow-tile partitions or by partitions made of light studs, metal lathing, and plaster. It has generally been considered—in commercial work, at any rate—unnecessary to protect a stairway carried on cast-iron strings, but the San Francisco fire showed that some form of protection is very essential. Where the inclosing partitions did not fail, the stairways were of course not seriously damaged, but as a matter of fact the partitions failed almost everywhere in San Francisco.

UNION FERRY BUILDING.

The Union Ferry Building (Pl. XLVI, *A*) is a large structure—practically of monumental proportions—which forms the terminus of all the ferry lines plying between San Francisco and various other points on the bay. It is built on piles, with heavy stone walls, backed with brickwork. The stone is the grayish-green sandstone elsewhere described. The floor construction consists of steel beams and girders, with stone-concrete slabs reenforced with expanded metal. The lower flanges or girders and beams were not protected. Near the center of the west front a high tower rises to a considerable distance above the building. The fire did not gain entrance, but the building was very seriously racked and damaged by the earthquake. The damage was not at all of a fatal nature, however, and the building was kept in practically continuous operation as a ferry terminus. The tower, which was built with a braced steel frame, inclosed to a height of several stories with a heavy wall composed of sandstone backed with brick, and closed in with wood and sheet metal above the masonry part, was so badly damaged that the masonry walls were being removed at the time of my inspection. To judge by the effects on this tower, the greatest intensity of the earthquake vibration must have been from northwest to southeast. The bracing was badly strained,

and in this case there can be no question that the effect was entirely due to the earthquake. The masonry in the tower was of an admirable quality.

In Pl. XLVI, *B*, is shown a crack in the brick masonry on the inside of the tower, together with a part of a diagonal tie-rod which had been stretched beyond the elastic limit and was hanging with a noticeable sag. It will be noted that the brickwork was well bonded and that the joints were well filled. The mortar was much harder than the bricks, but both were of good quality. It is also evident from this view that there was no general shattering of the entire mass; there was a well-defined crack, but nothing else.

At the northwest corner of the tower, about halfway from the roof of the main building to the top of the masonry walls of the tower, a diagonal tie-rod had been fastened to the wall girder by means of a gusset plate, with eight rivets in it. Seven of these rivets were sheared under the action of the earthquake, leaving the plate hanging by the eighth rivet at the time I saw it (Pl. XLVII, *B*).

One detail of the bracing in the ferry-building tower, of which a satisfactory photograph could not be procured, was as follows: The wall girders at the different floor levels were utilized for the wind struts of the bracing. In the lower part of the tower the diagonal tie-rods were fastened directly to the wind struts. The ends of the wind struts rested between upper and lower seats attached to the columns, and were, as a rule, bolted to each of those seats with nothing but two $\frac{3}{4}$-inch bolts, the idea evidently being that, as the struts resisted compression only, it was not necessary to fasten them to the columns with anything designed to resist any considerable force tending to separate them from the column. The upper seat was evidently designed to take the vertical component of the stress in the diagonal, and the lower seat to take this load in addition to the ordinary load which the wind strut transmitted to it in its capacity as a girder. The bolts fastening the ends of several of the wind struts to their seats had been sheared, and the struts had almost slipped out from between the seats.

In the upper part of the tower a different method was adopted, the diagonal tie-rods being fastened to bent plates that passed around the outside of the columns opposite the ends of the wind struts. No shearing of the bolts or slipping of the struts was noticeable at these points. It is plainly apparent that ordinary assumptions made in designing wind struts will not apply when it is desired that the bracing shall resist earthquakes. There is evidently a tendency for the columns at the ends of a wind strut to buckle outward, and thereby also a tendency to pull the strut out from between its seats. In fastening bracing to resist earthquake shock, therefore, the struts should be fastened to the columns at their ends much more securely than

is ordinarily done. In fact, if the diagonal is to be fastened directly to the wind strut, there should be a connection between the strut and the column capable of taking up the horizontal component of the stress in the diagonals. Knee braces, such as those used in the Call Building, possess a manifest superiority over ordinary bracket seats in construction of this sort. An examination of the condition of the bracing in the ferry-building tower can leave no doubt whatever that the tower was just on the point of total collapse. Conditions were so bad that the superintendent of the contracting firm that was taking the masonry down evidently felt a little uneasy about what would happen when the masonry covering was removed from the portion of the steel work where the bracing was most seriously damaged. He was proceeding with great judgment and caution, however, and no doubt succeeded not only in removing the damaged masonry with safety, but in so tying together the steel work as to avoid all danger of collapse.

A part of the masonry in the east front of the tower was precipitated from its position (Pl. XLVI, A) and fell through the skylight and onto the floor of the corridor in the upper story of the main building. This floor consisted of stone concrete, reenforced with expanded metal, and carried by steel beams with spans apparently of 7 or 8 feet. The contractor's superintendent, already mentioned, told me that he thought the amount of masonry so precipitated on this floor amounted to 30 or 40 tons. It punched in the floor one small hole not much larger than a man's fist, but nothing of any size got through. It is doubtful whether any form of floor arch or slab except reenforced concrete and possibly solid brick would have stood this test so successfully. Certainly no hollow-tile floor such as those in ordinary use would have stood it for a moment; the falling mass would have gone on through to the ground.

Along the west front of the ferry building, about halfway up the second-story window piers, most of the stonework had slipped about an inch. Some of the first-story piers were so badly shattered by the earthquake that they had to be boxed in to prevent the loose stone from falling. There were in the floor construction of the tower and of the building proper a few cracks which I thought might be due to the earthquake, although it is possible that they may have been shrinkage cracks. I was not able to get any convincing testimony on this point, but I have seen a good many shrinkage cracks and am of the opinion that most of these cracks were due to the earthquake and not to shrinkage. On the whole, the ferry building stood the shock remarkably well. It would seem to be the part of wisdom, however, to tear the tower down altogether and not to rebuild it.

UNION TRUST COMPANY'S BUILDING.

The ordinary steel-frame Union Trust Building, with terra-cotta fireproofing, came through the earthquake in about the same condition as the average fireproof building in Baltimore after the fire. From the exterior it presented the appearance of having stood the ordeal about as well as any other building in San Francisco that was completely gutted. The damage, however, was probably at least as great as that suffered by such buildings as the Continental Trust in Baltimore. Lower webs were off in many places, and column and girder coverings were damaged to a considerable extent (Pl. L, *B*).

MISCELLANEOUS STRUCTURES.

GENERAL DISCUSSION.

A number of buildings of fire-resistant construction in San Francisco, such as the Mutual Savings Bank, the Hibernia Bank (see Pl. XXXVII, *A*), and several others, have not been specifically mentioned in this report, but they presented nothing of more than ordinary interest. Detailed descriptions have been given of at least one example of everything that was typical, and practically everything described in detail was typical of many other cases of the same general class.

A building at First and Natoma streets had naked cast-iron columns, steel girders, reenforced-concrete beams from girder to girder, and reenforced-concrete slabs from beam to beam. The reenforcement of the concrete beams consisted of plain round rods passing through the webs of the girders and fastened with nuts in the same way as tie-rods. The aggregate of the concrete, in the beams at least, seems to have been of stone. Some of the slabs looked as if some cinders had been used in them, but this appearance may have been due to damage by the fire. At any rate the concrete was very badly damaged, as will be seen in some of the rear bays of the upper floor. Where the deflection was worst there may have been something precipitated upon the floor, but even at other points considerable deflection was apparent, together with serious damage to the concrete. It was evident, from the beams hanging down in the front, that in erecting this building the forms for the beams were filled first and the slabs were put on afterwards, so that there was no adequate bond between the beams and the slabs. The reenforcement of the slabs in this building was a very light twisted-wire mesh, and the only wonder is that it held as well as it did. The remains of a furred wire-lath ceiling were visible, and the failure of this ceiling is typical of what occurred in many other buildings.

It will be noted that there was no reenforced-concrete construction, pure and simple, in San Francisco. The warehouse of the Bekins Van and Storage Company (Pl. XXVII, *A*), in process of construction, had reenforced-concrete columns and floor construction and brick walls. The walls were badly damaged by the earthquake, but the reenforced concrete was absolutely uninjured. This building, however, was unfinished, and the lower portion of it was not subjected to the stresses which would have resulted had it been complete, with all its contents. In that case the energy due to the vibration of the greater superincumbent mass might have produced effects which were not produced in its unfinished condition.

One-half of the circular observatory on Strawberry Hill, in Golden Gate Park (Pl. XXIII, *A*), was thrown down by the earthquake. I did not make a personal examination of it, except from a distance, but was informed that it had been reenforced with heavy iron rods bedded in the masonry. It was reported to me that these rods were broken at the point where the collapsed portion had separated from the part still standing. The general effect of the earthquake on hollow circular structures of all sorts seems to have been a tendency to increase their diameter. Where this tendency was very marked, it naturally caused their collapse.

Practically all the other photographs submitted and not specifically referred to in the foregoing pages were taken with a view of showing earthquake damage. The tower of the church next to the old Mission Dolores was dangerously near being thrown down, and had to be pulled down later, as shown in Pl. XXIII, *B*. Pl. XXXVII, *B*, is a view of a brewery which had been four stories high, with a tower at the corner extending to a considerably greater height than the building. The damage was due to earthquake alone. Pl. XXI, *A*, shows a case of earthquake damage pure and simple. It will be observed that the face bricks were not bonded, and were thrown down in large quantities. None of the brickwork in this building seems to have been of a very good quality.

An old-fashioned brick building of ordinary construction near Fort Mason appeared to have survived the earthquake absolutely undamaged. This example indicates the variation in the intensity of the earthquake within relatively short distances.

Pl. XXXIII, *A*, shows a building, known as the Butler Building, which was partially completed at the time of the earthquake. When I first saw it the side wall, which appears in the illustration as nearly torn down, was standing at about the same height as the front wall (shown at the right side of the picture). This side wall had a few earthquake cracks in it which were plainly visible, but it was a matter of surprise to see, a few days later, that the wall had been practically torn down; for if this wall was damaged sufficiently to

justify its destruction, a great many walls of other steel-frame buildings ought to have come down also. This building was of the ordinary steel-frame type, without any bracing. The walls were very light, and on the principal fronts they were pretty well shaken to pieces. A superficial examination indicated that they were much more seriously damaged than the side wall which had been torn down. This building appears in the background of the view of the Dewey monument (Pl. XXX, A). At the time this view was taken a considerable amount of the masonry in the front wall had been removed, but there was still a great deal which, in my judgment, was too badly damaged to be safely left.

Pl. LV is a panorama taken from Pine and Powell streets. The building on the left side of the street at the left is the Merchants' Exchange. To the right, just behind the high ground and trees, is the Mills Building, and farther to the right is the Union Trust Building. The other buildings will probably be recognized by persons who are more or less familiar with the city; the names of the chief ones are given on the plate. It will be observed that this panorama covers an arc of nearly 180°. The Twin Peaks appear some distance to the right of the city hall.

ORDINARY BUILDINGS AND RESIDENCES.

The effect of the earthquake on miscellaneous buildings of the cheaper class was more or less interesting. There were a number of brick dwellings in San Francisco faced with arch bricks laid in Flemish bond. These bricks, of course, are considerably harder and stronger than ordinary red bricks. Though they make a very rough wall, it is interesting and attractive, like the old colonial brickwork in the East. Apparently these houses were very strong. Whether it was good luck in all cases, or whether this brickwork really was much superior to the average brickwork used in San Francisco, I saw not a single example of earthquake damage to any house built in this way. I noticed eight or ten of these dwellings, and not one of them was damaged. The same fact had been noticed by the enlisted man who accompanied me as a photographer. He apparently had seen a greater number of buildings of this kind of brickwork than I had, and he stated that not one of them seemed to have suffered any injury, although, in many cases, their neighbors had been seriously damaged.

A considerable number of frame buildings had practically collapsed under the earthquake; some of them were thrown bodily from their foundations. Plaster was generally shaken loose from wooden lathing, but, so far as I saw, none that was applied to good metallic lathing, such as heavy wire lath or expanded metal, had been shaken down.

As a result of my observations, I am inclined to think that a building of the following type would be very desirable for residential purposes in an earthquake country:

The frame should be of timber, rather heavy and thoroughly braced, with all the vertical members continuous from bottom to top, or else thoroughly spliced. The horizontal members should be made as nearly continuous as possible—preferably by full splices. Horizontal and vertical members should also be fastened together as rigidly as possible, diagonal braces being used wherever conditions will permit. The frame should be covered on the outside with expanded metal and this metal plastered on both sides, a good deal of cement being used in the plaster. The exterior can be finished in stucco or pebble dash, as desired. The interior of the frame should be covered with expanded-metal lathing and the ordinary interior plaster-finish put on. The ceilings also should be finished with expanded metal and plaster. In my judgment, a building of this sort could be put up for very little more than the cost of an ordinary frame dwelling, and would not only come through an earthquake much better, but would be very much more difficult to set on fire and would burn much more slowly after it was on fire.

CHIMNEYS.

Chimneys seemed to be shaken down by the earthquake everywhere; even where there was no other damage this result was almost universal. The chimneys, as a rule, were built of bricks laid in lime mortar, and generally broke off at the point where they came through the roof. Reenforced-concrete chimneys with a terra-cotta lining would be very little more expensive than the kind that were ordinarily used in San Francisco, and would have suffered very much less damage. If any chimney projects a considerable distance above the roof, it would be advisable to brace it near its upper end to the roof in some way, so that it would not be free to vibrate. It seems probable that this plan might have saved some of the chimneys that failed. Appearances seemed also to warrant the conclusion that in the vibration some chimneys were brought up short against the roof framing and thus caused to break off at this point. If there had been a little more room for relative vibration between the chimney and the framing, it seems possible that some of these chimneys would not have fallen. The best way to prevent such damage is to build the chimneys of reenforced concrete or of some other material that has both rigidity and great tensile strength. Such chimneys would not ordinarily break off, even though they jostled against the roof timbers.

BRICK SMOKESTACKS.

There were a great many brick smokestacks in San Francisco, nearly all of which suffered more or less damage. For some reason circular stacks seemed to suffer more than square ones, but the number of square stacks in evidence was not sufficient to justify general conclusions.

The views of brick stacks speak for themselves to a great extent. The stack of the Valencia street power station (Pl. LIII, *A*) was of some interest because of its peculiar cross section—an eight-pointed star. At the vertices of two diametrically opposite reentrant angles the stack was split practically from top to bottom. The ruins of a circular stack, situated near San Jose, are shown in Pl. XIII, *A*.

CONDITIONS OUTSIDE OF SAN FRANCISCO.

OAKLAND.

I made one trip to Oakland and went through the greater part of the town. A good many chimneys had been shaken down and the front walls of a number of ordinary brick buildings had been precipitated into the street. Several steel-frame buildings faced with sandstone were badly racked, and in places some of the stone had been shaken into the street. Some of the steel-frame buildings showed the same kind of damage as the Monadnock and new Chronicle buildings in San Francisco. The damage in Oakland in general was not different in type from that in San Francisco, but it was much less extensive, and individual cases were, as a rule, much less marked.

PALO ALTO.

I visited Palo Alto, and through the courtesy of President Jordan, of the Leland Stanford Junior University, was enabled to make a satisfactory examination of the damaged buildings at the university. These buildings represented in a general way three different types. Among them were some old buildings faced with yellow sandstone, which had been built in the early days by hired labor, under the supervision of Governor Stanford himself. All the sandstone used at the university was of a light yellow-buff color, rather soft, and apparently not very strong. In these older buildings, however, the cut stone had good wide beds, was carefully laid, was well bonded to the backing, and was solidly backed up with brickwork. These buildings were damaged seriously, but by no means beyond repair.

In addition to these older buildings there were some newer ones of the same general design, but the sandstone facing was thinner and the beds not so well cut nor so wide. The backing was not so good.

Much of it consisted of rubble made of very small pieces of stone, apparently gathered up where stonecutters had been working. Many of these spalls were not larger than a man's fist, and in places 4 or 5 square feet of the wall was entirely backed up with this material. The bonding of the stone facing to the backing seemed to be less thorough in the new buildings than in the old. In short, the newer buildings conformed rather to the modern commercial standard of building construction; the old ones approached the monumental. The newer buildings suffered materially more than the old. They were not, however, of a type that would indicate culpable negligence or incapacity on the part of anyone connected with their design and erection, although they were distinctly inferior in type to the older buildings. The mortar used was not by any means poor. It seems to have been lime mortar gaged with cement. I tried it at a number of points where the buildings had suffered very severely, and it was distinctly better than the average mortar found in ordinary commercial work, although not as good as straight cement mortar would have been.

The buildings of the third class at Stanford University were built of concrete. The girls' dormitory had concrete walls and timber interior construction, and in the central portion of the Leland Stanford Junior Museum, the oldest part of the building, the walls and interior construction were of reenforced concrete. There were two wings, built of brickwork, with reenforced-concrete floor construction. It is reasonable to suppose that the intensity of the force applied to this building by the earthquake was nearly uniform over the entire structure. The two brick wings were practically shaken down, suffering, I should judge, considerably more than 50 per cent damage. The reenforced-concrete central portion, viewed from the exterior, seemed absolutely undamaged. In the interior a few cracks had opened up, but they were not of serious consequence. I should judge that a thousand dollars would easily cover all the repairs to this part of the building. Its valuable contents were, to a large extent, thrown to the floors and smashed, involving a considerable loss; but the structure itself suffered almost no injury. The only damage to the girls' dormitory was caused by a chimney that toppled over and crashed down through the roof, doing some damage on the inside. By good luck, no one was hurt in this building. The concrete wall showed one or two cracks, which, however, were said to be shrinkage cracks that had appeared soon after the building was finished. The earthquake apparently had caused no visible damage of any sort in the exterior walls.

It was noticed that those buildings which had completely trussed roofs suffered much less than those in which the walls had to take

the thrust of the rafters. This result was naturally to be expected, and indicates that in earthquake countries walls should not be subjected to the thrust of the rafters at all. The damage at the university also indicated clearly the necessity of thoroughly tying all the walls to the roof construction, gable walls as well as others. The university post-office building was said to be of reenforced concrete and undamaged. Very good illustrations of the damage at Stanford University can be seen in the Engineering News for May 10, 1906, and in the Engineering Record for May 12, 1906. (See also Pls. XIV, *A*; XV; XVI; XVII, *B*; XVIII.) A concrete-block building in the town of Palo Alto was totally demolished.

OTHER TOWNS.

Concrete-block buildings elsewhere were also reported as totally destroyed. The various structures of the Southern Pacific Railroad along the coast division had suffered more or less damage. One or two stations faced with a sandstone similar to that used at the Leland Stanford Junior University, and built in the ordinary style, had been very seriously damaged. One station, which seemed to have been built a little more carefully and with larger stones than the rest, was in very much better condition than most of them. The city hall at Redwood had a central circular tower, with a dome supported on steel work, much as in the city hall at San Francisco (Pl. XXXI), though on a smaller scale, and suffered almost exactly the same kind and degree of damage.

FORTIFICATIONS.

I visited the old brick fort at the Presidio and also most of the batteries along the face of the cliff. There were a few cracks in the old brick fort, but nothing to indicate that they might not have been due to settling as well as to earthquake. An inspection of the new emplacements from the exterior showed no visible signs of damage whatever. As reports on these matters are made by officers especially in charge of the work, I did not attempt to make a detailed inspection of the fortifications.

RESERVOIRS, PIPE LINES, AND OTHER STRUCTURES ALONG THE FAULT LINE.

The following details were derived from a perusal of the report by Professors Marx and Wing, already mentioned (p. 63).

The Spring Valley Water Company had among its reservoirs two known as Crystal Springs Lake and San Andreas Lake. The line of the fault that caused the earthquake is said to run directly through both of these reservoirs. Crystal Springs Lake has a large and high concrete dam; it is also subdivided by an old earth dam that was

formerly the main dam, when the reservoir was smaller than it is now. The concrete dam, which was parallel to the fault and of course very near to it, was absolutely uninjured (Pl. XI, *B*); the earth dam, which lay across the fault approximately at right angles, showed definite signs of disturbance and lateral displacement. Longitudinal and transverse cracks appeared on top of the earth dam, and some of the former were reported to have extended to a depth of at least 3 or 4 feet. The transverse cracks were said to be less well defined and to indicate rather a general disturbance on each side of the fault line, about one-fourth of a mile away, and was absolutely to which it was damaged could not be ascertained.

San Andreas Lake is retained by a high earth dam. The fault ran under the east end of this dam and produced considerable disturbance over a strip about 150 feet wide, though the dam was not seriously injured. A concrete culvert inlet was connected with this dam, and one of the worst transverse cracks noted ran diagonally over the culvert, but the culvert itself was uninjured. Besides the high concrete dam of Crystal Springs Lake, the water company had another smaller concrete dam at Searsville. This dam also was parallel to the fault line, about one-fourth of a mile away, and was absolutely uninjured.

The Spring Valley Water Company had three main conduits running into San Francisco. One of these, known as the Pilarcitos conduit, consisted largely of 22-inch and 30-inch riveted pipe and 24-inch cast-iron pipe; some feeders were built of wooden flume. The conduit crossed and recrossed the line of the fault, and was so badly wrecked that the company has decided to abandon it—no doubt a wise decision, because the location along the line of the fault was a very bad one. Wherever the conduit crossed the fault line it was destroyed. In some places there was a longitudinal displacement of as much as 84 inches, which either telescoped the pipe or pulled it apart, as the case might be. (Views of these effects are given in Pl. IX.) It made no difference whether the conduit was in firm ground, or in soft ground, or carried on a trestle over marshy ground; the result was the same wherever it crossed the fault. In many places where the conduit was carried on trestlework the timber showed considerable decay. Whether sound timber structures would have withstood the shock seems open to question. (See also Pl. X, *A*.)

Within the city proper the reservoir known as Lake Honda was damaged by the cracking of its concrete lining. It is reported that this cracking was due to the displacement of a retaining wall by a sliding bank set in motion by the earthquake.

The distributing mains of the Spring Valley Water Company, wherever they passed through soft or made ground, suffered in the

same way as the conduits and pipes which crossed the fault line. (See the maps, Pls. LVI and LVII.) Some subaqueous pipe lines crossing the bay seem not to have been injured.

Two interesting earth dams are those at the San Jose Water Company's Saratoga reservoir, which lies in a saddle in the mountains and is retained by an earth dam at either end. The fault runs directly through the reservoir, crossing both dams approximately at right angles. It was reported that near the east end of the north dam transverse cracks were formed, which extended through the body of the dam. There was also a longitudinal crack on top and some settling of the upstream half of the dam. The reservoir seems to have been full at the time of the earthquake, but no evidence was found that any water had escaped through this dam. At the south end of the reservoir the fault line intersected not only the dam but the 10-inch outlet pipe, which was broken by the earthquake. Considerable damage seems to have been done to the dam by the water escaping through this broken outlet pipe. Whether the dam itself would have been seriously injured by the earthquake but for this pipe can not probably be determined.

Professors Marx and Wing also noted in the vicinity of the fault a number of monolithic concrete bridges, all of which were uninjured; none of them, however, absolutely crossed the fault line. (Cf. Pl. XI, A.) These observers also report that a small concrete reservoir, built partly in embankment and partly in excavation, was wrecked by the earthquake, and seem to think that such structures would better be built in excavation. They found that some high timber frames carrying water tanks, as well as similar structures supporting steel standpipes, were intact. A steel water tower at Santa Clara was wrecked. The engineer who designed this tower gives an explanation of its failure, however, in the Engineering News for May 10, 1906. Very probably his explanation is correct, and if so, there is no reason why steel towers should not be used. Doctor Jordan told me of one tower that he saw which had collapsed as a result of the earthquake, and in which the nuts on the upper ends of the anchor rods stripped the threads so as to allow the tower as a whole to be thrown over.

GENERAL CONCLUSIONS.

THE REBUILDING OF SAN FRANCISCO.

Unless future earthquakes are very much more severe than any that have occurred, there is no reason why the rebuilding of San Francisco should not be a successful commercial enterprise. It seems highly improbable that there will ever be earthquakes more severe than that of April 18, 1906. There is no doubt that the city can be rebuilt

so that, although it will suffer damage from future earthquakes, this damage will not be at all fatal, and the city will not burn up as a result of it.

DISTRIBUTION SYSTEMS FOR WATERWORKS.

In a city subjected to earthquakes it seems practically impossible to suggest any method of construction which will make the mains and distributing pipes at all times perfectly secure. In my judgment the only remedy is to have within the city itself a large storage capacity, distributed among various reservoirs, and to have a more than ordinarily complete gridiron of mains with gate valves to cut out any main at every intersection. Further, the mains should be larger than would ordinarily be required, so that if a portion of the gridiron were shattered it could be cut out, but the water could be brought in undiminished quantities to the perimeter of the shattered area from all undamaged parts of the gridiron; that is, the mains should be so large that, although the water would have farther to travel in this case, there would be an adequate supply for fighting fire, if necessary, in the area where the mains were shattered.

It would seem that in a city like San Francisco a special system of high-pressure salt-water mains, supplied from a pumping station, would be the best solution of the fire-fighting problem so far as the congested district is concerned. This plan has been recommended by the National Board of Fire Underwriters, and it is probably the wisest one under the circumstances. The pumping station should, of course, be protected from earthquake damage in every possible way. Perhaps it should be a floating station. The salt-water mains should be so laid out and so interconnected that nothing short of general destruction of the entire system could wholly shut off the water from any considerable area.

In a city like San Francisco, where there is practically no damage from freezing, it would seem worth while to run the mains exposed everywhere, so that breaks could be located almost immediately. As these breaks would ordinarily occur only in scattered localities, and would not be very great in extent themselves, it ought to be possible to repair them in time to prevent any general destruction of the city by fire. Running the mains exposed would, of course, introduce difficult problems at street crossings, but there is little doubt that such problems could be solved successfully if they were seriously studied. All this means greatly increased expense in the distribution system, but in a situation such as that of San Francisco it seems to be required.

The earthquake effects at San Francisco also indicate clearly that a special study should be made of the problem of promptness in emergency repairs to the conduits and mains. It seems certain that,

in the immediate vicinity of existing faults and near areas including any considerable amount of made ground, both conduits and mains may be expected to suffer serious damage. At one point on Van Ness avenue (see B, Pl. LVI), where I happened to see the mains uncovered, a heavy water pipe, apparently about 20 inches in diameter, had been broken into pieces not more than 2 feet long. The total length of the break, however, was not more than 40 or 50 feet, so far as I could judge from what I saw uncovered. It would seem that this main might have been spliced in a few hours had there been some means of rapidly plugging the broken ends on either side of the break and making a number of taps in the undamaged parts with parallel lengths of fire hose of large size. With gate valves at short intervals it ought to be possible to cut out any damaged portion of the system by connecting through with fire hose in such a way as to maintain at least a partial supply of water for fire-fighting purposes. Some similar plan on a larger scale might be devised for repairing conduits.

It would also seem desirable, wherever an important conduit or main crosses filled ground or material soft enough to suffer consolidation as a result of thorough shaking, to carry the main on piles or other foundations reaching to firm material below. Wherever there was filled ground the vibration due to the earthquake seemed to have much the same effect as would be produced in a vessel that had been loosely filled with sand and then subjected to vibration; as is well known, the sand, under such circumstances, will suffer consolidation to a very appreciable extent, which naturally lowers its surface by an amount corresponding in a general way to the intensity of the vibration. Where a large area and volume of made ground is subjected to similar vibration, subsidence occurs, and not only are buildings on the surface thrown down and destroyed, but water mains, sewers, etc., running through the filled material are subjected to a deflection which necessarily shatters them.

SEWERS.

The effect of the earthquake on sewers seemed to be practically the same as on conduits and water mains, except as varied by difference of material, where such difference existed. The necessity for firm foundations for sewers running through made ground is clearly indicated. The need of rapid repairs to the sewers is not quite so great as in the case of the fire mains, because a city can get along with inadequate sewerage facilities, if necessary. It would seem desirable, however, that all important sewers passing through made ground should be constructed of the heaviest iron or steel pipes, and be provided with an adequate foundation. Of course, sewers are not

under pressure, and therefore can not be repaired with fire hose, as suggested for water mains. There seemed to be some fear in San Francisco that the breaking of the sewers and the water mains would cause the water to be contaminated by the sewage; but evidently if means were devised to maintain a good pressure in the water pipes this pressure in itself would protect a leaky main from such contamination.

FIRE-RESISTING FEATURES OF BUILDINGS IN "CONGESTED DISTRICTS."

FIREPROOFING.

The Baltimore and San Francisco fires, as well as many other fires and fire tests, have proved conclusively that commercial methods of fireproofing are inadequate to stand any severe test. In most buildings the steel work is fairly well protected, but the number of failures is sufficiently great to show that the factor of safety against fire is not by any means what it should be.

For the protective covering itself to suffer complete destruction, or almost complete destruction, in any one fire is in itself a failure, because under such circumstances the steel work is very near destruction and the margin of safety is altogether too small. It is more than probable—almost certain, in fact—that a detailed investigation of all the buildings in San Francisco would reveal many "protected" columns, not indicated in this report, that buckled as a result of the failure of the covering. In my judgment, columns should either be covered with 4 inches of brickwork, laid in Portland-cement mortar, and have all of the interior space filled with concrete, or else they should be inclosed in an expanded-metal jacket and the entire interior filled with concrete, so that the minimum thickness of the concrete would not be less than 4 inches. Exposed flanges of girders and beams should be protected by the equivalent of 1½ to 2½ inches of solid porous terra cotta, according to circumstances. If concrete is to be used, this thickness should be increased by about half an inch. The protection for lower flanges should always be inclosed in a basket of expanded metal or heavy wire lath, securely anchored into the side protection of the webs. The San Francisco experience showed that, even in a hot fire, such metal-mesh basket work will largely retain its tensile strength, and thus hold in position the fireproof covering inside even though the latter should be shattered by expansion stresses or otherwise. The webs of the girders should be covered by 4 inches of brickwork or concrete, built up on the lower flanges. Girders should be completely covered from bottom to top before the floor systems are put in, so that the collapse of the latter will not expose the girder. Floor beams should have heavy, solid protecting

skew backs, not less than 1½ inches thick, or be covered with at least 2 inches of concrete. In an important work the protection of the lower flanges of the floor beams should also be incased in expanded metal or wire lath. The furred ceilings so much used in San Francisco are a valuable addition to the fire-resisting qualities of floor construction, and if the furring rods were more firmly secured the total loss here, as a rule, would be measured by the value of the plaster alone.

Hollow-tile partitions should not be less than 6 inches thick. The tiles should have webs at least 1 inch thick, and all interior angles should be well filleted. The tiles themselves should be carefully laid in Portland-cement mortar, with all joints absolutely filled. Timber studs running to the top of the partition, to frame a door or window opening, should be absolutely prohibited. The webs of floor tiles should not be less than an inch thick, and their interior angles also should be well filleted.

The results at Baltimore and San Francisco did not, by any means, indicate that either hollow tile or concrete is altogether a failure or altogether a success. Both fires indicated very clearly that commercial methods of applying both materials are inadequate, but also that successful results can be attained with both materials.

A conflagration never yields reliable comparative results, but judging from such comparative results as are available, I think that there is no question that the best fire-resisting material available at the present time is the right kind of burned clay—that is, a good, tough, refractory clay, almost as refractory as fire clay, made into proper shapes and properly burned. Some commercial hollow-tile work is made of good material, but, as a rule, that is the only good thing that can be said about it. There can be no question that good clinker concrete, made of well-burned clinker, Portland cement, and sand, is a very efficient fire-resisting material. It is better than anything except the better types of burned-clay products; but the cinder concrete commercially applied is, on the whole, no better than the flimsy hollow-tile work with which it competes; in fact, it is not certain that it may not be worse. The only way to determine this point would be to go through all the floor construction in a place like San Francisco and make tests of the load-carrying capacity, etc., after a fire. It is very doubtful, of course, whether such tests will be made.

If a hollow-tile floor, for instance, loses its lower webs, the damage is very apparent, yet most of such floors remain true and capable of carrying considerable loads. A cinder-concrete floor which is even more seriously damaged is very likely to remain true, for the reason that the fire which damaged it also removed its superimposed load before the damage was fully accomplished. A hollow tile which comes through a fire without losing any of its webs is as good as it

was before; whereas concrete of any kind which has come through a fire in which the temperature has exceeded 700° or 800° F. is inevitably damaged in all cases, owing to the dehydration of the cement, although it may appear uninjured to the casual observer. This property of concrete, of maintaining a good face in spite of real and serious damage, is likely to lead the layman into dangerous conclusions, and consequently into equally dangerous practice. It would seem that wherever reenforced-concrete floor construction is used a furred ceiling below it should be absolutely required.

The furred ceilings ordinarily used are too light; the furring rods are not quite heavy enough and they are not adequately secured to the floor construction above. If they were made a little heavier, and were more firmly secured, it is probable that, as a rule, no loss would occur except that of the plaster. Even if the furred ceiling comes down bodily, this failure is not apt to occur until so late a stage in the fire that the floor construction above will be practically undamaged, because there will not be enough left of the fire to raise the temperature of the concrete to the point where dehydration of the cement will begin. The presence of a furred ceiling, however, no matter how good, should never be accepted as an excuse for omitting the protection of the lower flanges of the floor beams and girders. A hollow-tile floor that would be fully equivalent to a reenforced-concrete floor, with a furred ceiling, could be made by using tiles in which the minimum thickness of the webs is 1 inch, and of which the material itself is tough, refractory clay, made porous by the addition of sawdust; such tiles should, however, be burned to a point where the clay itself is just short of vitrification. All the interior angles, where the webs of the tiles join each other, should be rounded to a radius of at least 1 inch or 1½ inches. If necessary to secure proper burning, a small hole three-eighths to five-eighths of an inch in diameter might be allowed through the mass of clay at the intersection of the webs.

Tests recently made of a pattern of tile used at the War College indicate that floor tiles subjected to a fire test will stand better if there is but one interior hole through the tiles, all the material which would otherwise be used in the interior webs being concentrated in the outer webs, and the opening in the tile being of circular or elliptical shape, depending on the height and width of the tile. For floor arches between steel beams such a tile as this one would have to be used on the end-construction plan. A specially heavy skew back should be designed to go with it, or else the end tiles should be cut to fit the profiles of the beam. The tiles themselves being so heavy, the latter method of obtaining a skew back would probably make the arch more than strong enough to carry its load, and where carefully done might afford adequate fire protection to the beams,

although for that purpose a specially designed extra heavy side-construction skew back would be better, and should on the whole be recommended even in connection with the heavy end-construction arches described. It is probable that either a good concrete floor with the right kind of ceiling below it, or a heavy tile floor such as that herein described, would come through almost any fire with no damage except the loss of the ceiling plaster. These two types may therefore be taken as equivalent in efficiency; they will probably be about equal, also, in first cost.

It should be added that attic floors and roofs should be as carefully designed to resist fire as any other part of a building. This is a thing that has rarely been done, and the experience of both Baltimore and San Francisco shows that it is absolutely necessary.

PROTECTION OF OPENINGS.

While there is no doubt that commercial standards of fireproofing are dangerously inadequate, the greatest trouble of all is the fact that so little attention is paid to protecting the exterior openings in a building. Even a very inefficient type of fire shutter would probably have saved some of the buildings in San Francisco, which were, as a matter of fact, burned out. A light metal shutter combined with a window sprinkler would probably resist a rather fierce fire for a long time. Although the failure of the water supply in San Francisco might be urged as one reason why a window sprinkler would have been of no avail, it is a fact that water can be obtained by driving wells into the sand which underlies the business portion of San Francisco almost everywhere. Under these circumstances, if the fireproof buildings had been fitted with metal shutters, even no better than those in the windows of the hall of records, and if each window had been provided with a sprinkler and the building itself with its own well and fire pump, it is probable that the fire could have been kept out of a large number of the buildings. The protection of external openings is by all odds the most important constructive problem involved in the efforts to make cities proof against conflagration, and it seems probable that at the present time adequate protection of windows and doors is available at a reasonable cost. In my judgment, windows protected in the following way, even without sprinklers, might keep out the fire, though the buildings were shut up and abandoned.

1. The outer opening should be protected with some form of rolling steel shutter or, preferably, with a shutter composed of sheets of steel sliding in very deep rebates in the walls. The sheets of steel should be anchored in these rebates by means of angle irons or rivets driven so as to interlock with a bead to be placed in position after

the sheet of steel is itself in position. By providing a pocket in the masonry just above the window head and making these shutters in three or four parts, overlapping and interlocking at the overlap, the whole shutter could be slid up into the wall practically out of sight. This arrangement would necessitate window openings slightly lower than those used in many commercial buildings, but the loss of light would not be very serious. The metal shutters when closed should overlap the window opening in all directions by at least 6 inches. This overlapping could be accomplished at the sill without making a pocket to catch water and dust, by forming a step in the sill itself.

2. The windows should be made entirely of wire glass, with sheet metal or metal-covered sash, hung in metal or metal-covered frames. Clear wire glass can be used if desired.

3. On the inside of the window there should be a sliding shutter, either of wood covered with sheet metal or of sheet metal such as that described for the outside. If the outer wall is furred, a pocket could be made between the furring and the wall, so that the inside shutters could be slid sidewise.

It is probable that under a fairly bad exposure to fire the outer shutters here described would be so damaged that they would have to be removed. In a conflagration they would probably be warped to such an extent as to let the heat in, and possibly to soften the wire glass and damage the windows themselves, so that they also might have to be renewed—at least so far as the sash were concerned. But it is very doubtful if any conflagration would ever get through the sash, much less through the inside shutters. Any damage to the window protection, however, would be a very small matter compared with the total destruction of the contents of the building and a damage of 65 to 80 per cent to the building itself.

Window protection of the kind just described could be so designed that it would not be objectionable even on the principal fronts of buildings. The San Francisco and Baltimore fires have demonstrated that all the exterior openings of even fireproof buildings need protection. It would seem that the time has arrived when building ordinances should require it.

If to the triple window protection described above a window sprinkler with adequate water supply is added, a defense which will probably not only be adequate for its purpose, but which will suffer small damage itself, will be provided. This system of protection, while it has never been applied, can be applied at a cost which is not prohibitive, especially if unnecessary and expensive finish is omitted.

Practically all the fireproof buildings in San Francisco were unshuttered. Many nonfireproof buildings were partially shuttered, but no building, except that of the Pacific States Telephone and Tele-

graph Company on Bush street, was completely shuttered. Although every opening in this building was protected, it is not certain that the fire did not find its way into the building through some of them in spite of the protection. The protection of individual openings apparently was not quite heavy enough.[a]

The view of the main front of this building (Pl. XLI, *A*) shows plainly that it was not severely attacked by the flames, yet it probably would have resisted such an attack a good deal better than the façades of many other buildings. The exterior architraves of most of the windows are of solid molded brickwork, and the amount of hollow terra cotta in the exterior front is reduced to a minimum, so that this building would probably not have suffered quite as much as the average, even if the fire test from the outside had been fully as severe.

FIREPROOF VAULTS.

It would seem that the question of so-called fireproof vaults in commercial office buildings should also receive some attention. The failure of such vaults in San Francisco is absolutely inexcusable. The fact that they were so flimsy was not due to any lack of available knowledge as to how a fireproof vault should be built; the only motive that can be imagined for the erection of such vaults is parsimonious and criminal economy. (See Pl. LII.)

CONSTRUCTIONS AND MATERIALS RECOMMENDED FOR EARTHQUAKE LOCALITIES.

For every tall building the best type of construction is undoubtedly a steel frame, but it should be thoroughly braced in much the same way as in the Call Building, where the steel bracing undoubt-

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[a] Since the above was written the following information has been received from California, through the courtesy and cooperation of Capt. M. L. Walker and Capt. William Kelly, both of the Corps of Engineers:

The rolling shutters on the Bush street building of the Pacific States Telephone and Telegraph Company were made of interlocking slats crimped out of heavy sheet iron, the shutter as a whole sliding at the sides of the opening in heavy iron guides. Captain Kelly thinks they were made of No. 22 iron. I do not believe, personally, that these shutters withstood the direct impact of fierce flame for a great length of time; they would have warped and pulled apart so as to let the flame in. The view of the Bush street front of this building (shown in Pl. XLI, *A*) would indicate that there was no direct attack by the flame from the outside, and there is every reason to believe that the plate glass on the inside stood long enough to prevent the shutters from receiving any serious attack from the flames of the interior fire. It is probable, however, that these shutters are fully as efficient as the rolling shutters made by other manufacturers out of continuous sheets of corrugated iron riveted together along the edges. The continuous sheets have to be of rather light metal, in order to make them practicable; and when subjected to any great amount of heat they invariably pull apart along the lines of rivet holes—a weakness which was clearly illustrated in the Baltimore fire. There would seem to be no doubt, however, that rolling shutters of either type used on the outer windows of a building would effectually prevent ignition from radiant heat due to a fire in a neighboring building. They would also, of course, resist for a time the actual impact of flame, but I am personally of the opinion that they could not resist this form of attack for very long.

edly saved the masonry. In such buildings as the new Chronicle and the Monadnock the effect of the vibration was really resisted by the masonry, which was much shattered. Some of it was precipitated into the street from the new Chronicle Building, the Rialto Building, and others. It is not at all certain that the steel frames of these buildings have not also been seriously damaged by the earthquake. Naked steel frames of the same type came through without serious damage, but they did not suffer the additional stresses due to the vibration of a great load of masonry, floor construction, and contents in the upper stories, as did the finished buildings. It is not right to run the risk of precipitating the masonry into the street on the heads of passers-by, as would have happened at the unbraced steel-frame buildings had the earthquake occurred at a later hour in the day. Besides, if the strength of the building is dependent on the masonry, which is seriously shattered by the stresses that it is expected to resist, the factor of safety against general collapse is manifestly too small. The steel-frame construction should therefore be thoroughly braced. In my judgment, to obtain the best results it should also be inclosed with walls of reenforced concrete, in which case it would be almost impossible to throw the walls off. The proper artistic treatment of this material in a place like San Francisco would seem to be a very important problem for the architects. The great utility of reenforced concrete in earthquake shocks can not be denied. Where steel-frame buildings are to be finished with ordinary masonry walls, however, complete bonding of all face bricks with full header courses should be absolutely required. No other form of bond is adequate. Nothing but Portland-cement mortar should be allowed in any part of the structure. The masonry should be tied to the steel frame in the very best possible way, and much more securely than is ordinarily the case.

For buildings of moderate height, say up to 125 feet as an extreme limit, reenforced concrete alone can undoubtedly be so designed as to give very good results when subjected to either earthquake or fire. But the bracing of a reenforced-concrete building of any height to resist earthquake is a matter for serious study. The problem can be solved, but it has not been solved yet.

Any building of considerable height, in an earthquake country, should have as little mass in the superstructure as possible, consistent with other necessary qualities. But this limiting of mass does not mean that the flimsy floors and partitions heretofore in use should be continued. In fact, to make the buildings proof against both earthquake and fire it is probable that they will have to be at least as heavy as they have been, but changes in distribution of the mass could advantageously be made.

For the ordinary commercial building, where brick walls and wooden joists would ordinarily be used, I am of the opinion that the use of reenforced concrete would be the safest and most practicable solution in a place like San Francisco. Where reenforced concrete is used throughout, whether the building is very tall or not, great care should be taken with the design and execution of the connections between the columns and the members of the floor system. There should be heavy knee braces for the connection of all girders and beams, and, wherever possible, portal bracing in the shape of reenforced-concrete arches should be introduced. Of course the amount of this work that needs to be done depends on the circumstances in each individual case, such as the height of the building, its horizontal area, the kind of material, the dead weight in the upper stories, etc.

The opposition of the bricklayers' union and similar organizations has hitherto prevented the use of reenforced concrete in San Francisco for all parts of buildings. This action of the labor unions has probably cost the city a good deal, and, should it be continued, will cost a great deal more in the future.

From the effect on the fortifications, and on monolithic and massive concrete structures elsewhere, as indicated by the details taken from the report of Professors Marx and Wing, it seems justifiable to conclude that a solid monolithic concrete structure of any sort is secure against serious damage in any earthquake country, unless it should happen to lie across the line of the slip; in that case the damage might be fatal, or it might not, depending altogether on the amount of the slip and the intensity of the forces that accompanied it.

It would seem that earth dams of ample size and with good foundations are also secure against fatal damage unless they are traversed by the slip. Even in the latter case the damage would appear to be not always fatal; that it would never be fatal, however, would be a rash assertion to make. It is unsafe to say that any sort of structure could be built so that geologic faulting could occur immediately underneath it without doing serious damage. As a matter of fact, however, most structures in an earthquake country would not lie on the line of a fault, and it seems quite certain that in such cases well-constructed earth dams and solid monolithic masses of concrete, whether large or small, would escape serious injury.

THE MINIMIZING OF FIRE LOSSES.

A study of the results of the Baltimore and San Francisco fires, especially in connection with the statements of adjusted losses at Baltimore, readily discloses the following facts:

In the first place, the contents of the fireproof buildings were a total loss. In many buildings the contents might probably be worth

more than the structure itself, especially if any attempt is made to fix the value of records and papers that can not be duplicated. In the second place, the buildings themselves suffered a damage exceeding 65 per cent, and in San Francisco probably amounting to almost 80 per cent. A study of the items entering into this damage discloses the fact that a very large proportion of it is due to the loss of the architectural finish, such as face brickwork, ornamental terra cotta, and stonework on the exterior; marble dadoes, columns, and other finish on the interior; wooden door and window frames, wooden doors and windows, ornamental grillwork, etc. If the fireproof-building problem is to be solved in such a manner that conflagrations will not cause serious losses, it would seem that radical revision of the method of finish is necessary. As the finish must practically be a total loss anyway, it should be so devised that it can be replaced at small expense. This requirement, however, makes it impossible to adopt a material for the construction which, as the architects say, finishes itself—because, if the exposed surface is destroyed, the material becomes a total loss. It would seem that for the exterior of the structure, walls well built of good, common brick, laid in Portland-cement mortar, or else of reenforced concrete, could be finished on the outside with stucco, pebble dash, or some similar material. The opportunity for the effective use of colors here would be very great. If the buildings were exposed to a fire, the exterior finish would probably be a total loss, but its value in dollars and cents is small. The fire might even strip it off and cause serious spalling to the main wall underneath, but, even so, the operation of renewing the finish would furnish adequate repairs for the main wall itself. On the other hand, if face brick or stone or ornamental terra cotta be spalled, the loss is total; the original finish can not be renewed, except by tearing the wall down and rebuilding it. On the interior, combustible trim of all kinds should be eliminated and marble or stone finish should be securely protected from the access of fire. Enameled bricks and enameled tiles should also be made secure against not only the direct access of fire but the effects of high temperatures however applied. Instead of marble wall finish or enameled bricks or tiles, wall plaster of a good quality, finished with enamel paint, furnishes a perfectly satisfactory substitute, so far as utility and sanitary qualities are concerned. If such finish is destroyed by fire, its renewal is a matter of relatively small cost.

All interior partitions should be so solidly constructed that there would be no question whatever of a fire ever getting through them. That ought to be absolutely impossible. Stairways, stairway halls, and other places where elevator grills, ornamental balustrades, etc., might be used should be so located that no fire would ever get into them, and they should be kept absolutely free of combustible matter

of all sorts and descriptions. Wooden floor finish should not be allowed in any portion of the building. All doors, door frames, window frames, and window sash should be of metal or of wood covered with metal. All important openings should have doors on both sides of the wall, the idea being to so design the interior of the building that a fire starting in any one room could be left to burn itself out not only without being communicated to other rooms or to the corridors, but also without causing any great money loss to the building itself in the room or rooms where the fire occurs. The interior construction of the building should be such that, should a fire by any chance be introduced from the outside, it could be confined absolutely to the room or rooms to which it finds access. Such a thing as a conflagration sweeping through a building can be made impossible at reasonable expense, provided unnecessary architectural finish is omitted and the money ordinarily expended on it is applied to other things.

Even such a building, however, might have a shutter left partly open, or some other of the various fire-resisting devices might be left in such condition as to defeat the purpose for which it was installed; so that if the building contains a large amount of combustible contents, it should still be provided with sprinklers. The municipal water supply should be under sufficient pressure to supply the sprinkler system. In a city like San Francisco an artesian well and fire pump in each building should be provided for the same purpose, if possible. Even then, if there is a conflagration raging, the mechanical staff of the building and as many more men as can be obtained should be kept on duty inside the building, watching for points of weakness and extinguishing fires should any begin. A small amount of water and a small force of men would suffice for this duty in a building constructed as described.

It appears that in San Francisco a number of owners who were organizing forces for the active defense of their buildings were driven out by the police and military authorities in accordance with instructions from the municipal authorities—no doubt to prevent looting and also with a view of saving people from the effects of the dynamiting. It would seem, however, that in some cases proper judgment was not exercised, and that some buildings might have been saved themselves and might also have acted as barriers to the further progress of the flames if their occupants had been permitted to carry out their plans. For good illustrations of what can be done in this way one need point only to the post-office building, the mint, and the appraisers' stores. There is also every reason to believe that a more or less active defense was carried on in the Kohl Building; otherwise it must have suffered more severely than it did. As it was, however, this building was saved with slight damage.

A fire-resisting building is, in one sense, exactly analogous to a fortification—it needs a garrison to make it thoroughly effective. There is this difference, however, that a fire-resisting building can be made so effective in itself that a relatively small garrison can save it. In my judgment, a building thoroughly well constructed along the lines indicated in this report would stand in a conflagration such as that which occurred in San Francisco, preserve its contents, and suffer a loss to its own structure and finish not exceeding 15 per cent. Until a result approximating this degree of endurance is achieved, it is hardly fair to say that the "modern fire-resisting building" is a success, except in so far as it enables a sufficiently tall structure to be erected on a piece of valuable real estate to furnish an adequate return for the entire investment, and even this statement is true only as long as the building does not happen to be attacked by a conflagration.

EARTHQUAKE INSURANCE.

It would seem that in a place like San Francisco it would be sound policy for the business men to form a mutual earthquake insurance company on lines similar to those of the mutual fire insurance companies. They should employ competent experts to draft specifications and evolve types of designs not in conflict with the municipal ordinances for buildings specially planned to resist earthquake. To be admitted to the benefits of the mutual earthquake insurance company an owner should be required to conform to the standard plans and specifications. In my judgment, there is every reason to believe that such an enterprise could be made successful and that it would result in having available at all times a fund for making good any earthquake damage. It is probable that the premiums that would have to be charged by such a mutual insurance company would be found to be no greater than those that are charged for fire risks in large cities.

SUMMARY.

It will be apparent that much of the information presented in a report like this one is necessarily hearsay. So far as the history of the fire is concerned, this indefiniteness can not be avoided, and the details of the damage itself could be verified only by a prolonged stay in the ruined city and a close inspection of the ruins of every building at every stage of the process of cleaning up. It is to be hoped that the technical men engaged on this work will keep a complete and accurate record of all details of every sort, which will be available for future reference. It is believed, however, that enough evidence was collected at first hand to abundantly justify every con-

clusion and broad statement contained in this report. The only doubt in my mind is whether the damage may not have been really greater than it appears.

Extreme caution should be observed in drawing general conclusions from any individual case of damage in a great conflagration. For instance, the way in which misleading conclusions can readily be reached is indicated in the discussion of the relative merits of terra cotta and concrete for fireproof floor construction. The records of the fire, rightly read, would prove that both concrete and burned clay are efficient as materials, but that the method of application of both is open to severe criticism. That hasty and ill-founded conclusions have been reached is only too evident from the articles which have appeared since the San Francisco disaster.

It is also necessary that extreme caution should be observed in drawing conclusions in regard to the effect of the earthquake. Reenforced concrete proved itself superior to brickwork beyond any doubt. There is every reason to believe that for buildings of moderate height reenforced concrete can be so designed that it will be quite as efficient as a steel frame; but it should be remembered that this proposition was not proved, because there was no reenforced-concrete building of considerable height in the entire district affected. Again, the fact that steel frames stood up during the earthquake does not prove that they are earthquake proof. The framing of the tower of the Union Ferry Building suffered almost fatal damage, yet it stood up. The Call Building proved the efficiency of stiff and adequate steel bracing; but many of the other commercial steel-skeleton buildings showed very clearly the need of it. The fact that some of the tall buildings are now out of plumb is no proof that they are damaged; very few such structures ever are plumb, and if the deviation is not very great it is quite possible, even probable, that the building was erected out of plumb. The condition of the masonry in wall piers, however, gives ground enough for uneasiness. It is safe to say that a well-braced steel frame is proof against ordinary earthquakes, but to point to the actual commercial steel-frame structure in San Francisco as a triumph of the ordinary type of steel frame, in advance of the careful detailed inspection of the steel work by competent engineers, is premature, to say the least.

THE EARTHQUAKE AND FIRE AND THEIR EFFECTS ON STRUCTURAL STEEL AND STEEL-FRAME BUILDINGS.

By Frank Soulé.

THE EARTHQUAKE.

GEOLOGIC FEATURES.

On the morning of April 18, 1906, central California experienced an earthquake, the most severe, as measured by its results, in the history of the State. The seismograph in the observatory of the University of California, at Berkeley, recorded the shock as beginning at 5 hours 12 minutes 6 seconds a. m., Pacific standard time, and as lasting for one minute and five seconds. Its severity was afterwards estimated and rated as IX in the Rossi-Forel scale of earthquake intensities. Other minor shocks followed immediately and at short intervals, so that before 7 p. m. of the same day thirty-one of these had been registered at the observatory. Slight shocks, coming successively, after longer and longer intervals of time, were experienced during several weeks following, until finally the earth's crust in California seemed to have readjusted itself to new conditions of pressure and equilibrium. The material damage from the earth tremors was inflicted by the first great shock. The minor ones following wrought no injury, except to throw down a few tottering walls that had been racked by the original earthquake.

For many years the leading geologists in California have known that a rift, or line of dislocation in the earth's crust—called in common parlance an "earthquake crack"—starting near Point Arena, extends in a straight line, at least 400 miles in length, in a direction S. 35° E. (fig. 1, p. 3). Passing under the ocean bed 8 miles west of the Golden Gate, the rift cuts the shore again at Mussel Rock, runs along the reservoir basins of the Spring Valley Water Company and over the Coast Range of mountains, ignoring surface topography in its course, and extends at least to Mount Pinos, in Ventura County, and probably still farther to Lake Elsinore, in southern California. This great "fault" gives abundant geologic evidence of having been, in the remote past, the locus of many distinct earthquake movements and disturbances.

It was a rupture and slip along this fault, plainly evident for nearly 200 miles, that shook so violently the thousands of square miles of the earth's surface in central California. The first snap and movement of the crust were registered at the observatory of the State University as proceeding from south-southeast to north-northwest, or about parallel to the fault. This movement was there recorded as over 3 inches horizontally, and was accomplished, as estimated by the California earthquake investigation commission, in one second of time. The vertical movement at the same place and time was believed to be about 1 inch. Professor Omori, the distinguished Japanese seismologist, also estimated the vibration in San Francisco to be 3 inches in one second.

Instantly following this first snap were rebounds, reactions, and terranean reverberations from all parts of the greatly disturbed area on either side of the fault trace, which made the record on the seismograph resemble a tangled spider's web. It was this part of the earthquake—the temblors—that created and continued the racking vibrations, the twistings, and the wrenchings that brought down chimneys, walls, and towers.

Members of the California earthquake investigation commission advanced the belief that the first break, slip, and shock in the crust began at the northwest extremity of the fault trace, and that from this point the rupture and shearing extended progressively toward the southeast. This view seems to be borne out by later investigations, and certainly the greatest disturbances on the line of the fault were at and near its northern extremity. The earthquake was felt to a greater or less degree over a vast extent of territory, stretching from Coos Bay, in Oregon, to Los Angeles, in southern California, and from western Nevada over the greater part of middle California, and even out to sea. Although not noticeable to the senses, it was recorded on seismographs in Washington, D. C.; Tokyo, Japan; and Potsdam, Germany.

A STUDY OF THE EFFECT OF NATURAL FEATURES ON THE INTENSITY OF DESTRUCTION.

DISTANCE FROM THE FAULT LINE.

The actual area of destruction was about 400 miles long (from north to south) and 50 miles wide on either side of the fault trace. The destruction wrought by the earthquake in its severe effects was proportional in a way to the nearness of the locality to the fault trace, but varied greatly according to the character of the rock and soil formation throughout the disturbed area.

Directly on the fault trace the disturbance and destruction were at a maximum. Many buildings and other structures were wrenched,

twisted, and thrown down (Pl. X, *B*); fissures were opened in the earth (Pls. III, IV); trees were uprooted and thrown to the ground, or snapped off, leaving their stumps in a standing position, or split from the ground up through the stock to the branches (Pl. II). Roads were ruined for long distances, bridges were thrown off their abutments (Pl. XI, *A*), and water pipes were twisted, telescoped, collapsed, or broken (Pls. IX; X, *A*). Along the seashore immense landslides occurred, throwing vast quantities of earth and rock into the sea. (See also Pl. VIII, *B*.)

The main pipe lines of the Spring Valley Water Company, which were depended on exclusively to supply the city of San Francisco with water, as well as the distribution system of this company in the city, were broken in many places, and the supply of water was absolutely cut off for a number of days after the earthquake (map Pl. LVI). The great mains leading from Pilarcitos, San Andreas, and Crystal Springs lakes were all badly broken (Pl. LVII). The Pilarcitos conduit in particular, which ran almost along the fault trace, was completely ruined and rendered unfit for repair (Pl. IX). The great 44-inch water main crossing the San Bruno marsh was thrown down from its supporting trestles in a serpentine line, and broken in several places.

As the distance from the fault trace increased, the violence of the disturbance in a general way diminished, but this statement must be modified by saying that in cities and towns built upon the alluvial soil of valleys the destruction was at its greatest, as, for instance, at Santa Rosa, about 20 miles east of the fault trace, in the Sonoma Valley (Pls. XIV, *B*; XVII, *A*). This city, built upon a deep, alluvial soil, was more severely shaken and suffered greater damage, in proportion to its size, than any other town in the State. Scarcely a brick or stone building in the town was left standing, and 80 people were killed.

SOIL FORMATION.

The destruction wrought by the earthquake amounted to little or nothing in well-built structures resting upon solid rock, and, all other things being equal, increased in proportion to the depth and incoherent quality of the foundation soil. Thus dwellings in Berkeley, upon the solid rock, were scarcely disturbed, while those on the level plain of Oakland, 4 miles distant, were severely shaken and injured, as, also, were the buildings at Leland Stanford Junior University (Pls. XIV, *A*; XV; XVI; XVII, *B*; XVIII), 7 miles distant from the fault trace; at San Jose (Pls. XII, *B*; XIII, *B*), 13 miles distant; and at Agnew (Pl. XIII, *A*), 12 miles distant. The town of Salinas and the alluvial valley of Salinas River were also severely shaken. This region was fissured and disturbed more than any other district in the State.

In order to get a fair understanding of the effects of the earthquake in San Francisco, a knowledge of the geologic formation and the different soils constituting the foundations of structures is necessary. The city and county of San Francisco comprise the northern extremity of a long, narrow peninsula, lying south of the Golden Gate, between the Pacific Ocean on the west and the southern half of San Francisco Bay on the east. (See map, Pl. LVII.) The boundary line between this county and San Mateo County lies about 8 miles south of the Golden Gate. The area of San Francisco County is 46½ square miles. The population of the city on April 1, 1906, was estimated to be 460,000.

The site of the city has at least four different soil formations. Around the Bay of San Francisco, from Telegraph Hill to Mission Creek, which runs from west to east and empties into the bay, and on both shores of the creek is a strip which was originally mud flats and overflowed lands, having an area of about 354 acres. These tracts have been gradually filled in (especially on the bay shore and the northern Mission Creek sides), since the days of the American occupation, by encroachments on the water front, due to business and commercial pressure, and wharves and docks, warehouses, factories, manufacturing establishments, and large wholesale houses have been built on these filled-in lands. At the present time these large areas are for the most part included within the sea walls running around the officially established water front nearly as far as Mission Creek. They are known as "made lands," and consist of deep layers of mud, in many places saturated with salt water, and overlain by sand, trash, etc., which has been filled in upon them.

On this soil were built nearly all the commercial and wholesale business structures of San Francisco—such as the Union Ferry Building—many large hotels, the post-office, the branch mint, and similar structures. On the Mission Creek side were originally very large areas of marshes that have been filled in with sand from adjacent hills. Adjoining all these made lands is the comparatively level ground, composed of a natural mixture of sand and clay, formed by the wearing of the hillsides and by the incoming of sands drifted from the seacoast. Upon this fringe of soil next to the made lands were built many of the largest hotels, tall office buildings, and expensive structures of brick, stone, and steel.

A ridge of rocky hills runs from the northeast corner of the city, or Telegraph Hill, southwestward along Russian Hill, Clay Street Hill, and so on, to Sutro Heights. These hills are composed largely of indurated clay, shale, and, on their highest summits, serpentine and other rocky formations. A ridge of sand hills runs through the western and southwestern portions of the city to the Pacific Ocean. The slopes and summits of the hills nearest the business portion of

the city are closely built residence districts, and the areas toward the Pacific Ocean are covered with cottages, more and more sparsely placed, to the boundaries of the county.

Adjoining the business district on the southwest side, along Mission Creek, on the flat sand lots, was another thickly populated residence section known as "south of Market street." It was occupied almost exclusively by wooden buildings.

More than 90 per cent of the buildings in San Francisco were of wood. Almost all the brick, stone, and steel structures were in the congested business portions of the city, upon or very near the made land. Even in this district there was a large percentage of wooden buildings. High steel structures of the most modern type have been erected only recently in San Francisco, and the number of them is small, not exceeding 50.

The most destructive effects of the earthquake in San Francisco were experienced upon this made land. Wherever buildings were well founded on wooden piles deeply driven into the mud—as, for example, the Union Ferry Building—these foundations were disturbed but little or not at all; and where the superstructure had been well and strongly put up, practically no damage resulted. Only in poor foundations laid directly upon "filled-in" ground on the raft principle, or in buildings that were poorly constructed or underpinned or had a weak frame, poor brickwork, or brick laid dry in poor lime mortar, was there serious damage or collapse.

The Union Ferry Building (Pl. XLVI, *A*), with the exception of its high tower, was little injured, and the level of its floors was not perceptibly changed. At the same time, the streets at its front, which rested simply on the made soil, were rolled into waves 3 or 4 feet in height. So far as the writer is aware no foundations that had been properly established were in any considerable degree injured by the earthquake; nor was any structure of brick or stone, iron or steel, that was well designed and constructed, greatly damaged. Some chimneys and cornices were thrown down, but until the fire had passed over the region the structures remained ready for use. This statement applies especially to the wooden-frame structures throughout the residence part of the city, where the only losses were those of chimneys and plaster.

On the made land in the business portion of the city there had been erected in early days many light wooden buildings, which rested on simple timber underpinning founded on the filled-in material. Many of these structures collapsed, but this result was due to their imperfect foundations and weak construction rather than to the severity of the earthquake. Numerous structures in this district had been built of dry brick or stone laid in common lime mortar, and their beams, girders, and columns had not been anchored to the

walls. Such walls commonly collapsed, and the brick were found afterwards with dry, clean surfaces, the mortar having no adhesion. (See Pl. XXI, *A*.) On the other hand, walls that had been laid in Portland-cement mortar, with brick thoroughly wetted and all parts well bonded together, stood the trial perfectly and are standing to-day.

Tall, steel-frame, stone-exterior office buildings of the class A type that were founded either on well-driven piles or on concrete slabs suffered no very serious injury by the earthquake. With the exception of a crack here and there in a stone pier, arch, or stairway, or a block of veneer loosened or dropped from a front, they remained entirely serviceable, so far as the earthquake effect was concerned. An excellent example of this class of buildings, and one that is exceedingly instructive, as it passed through the earthquake but escaped the fire that ravaged San Francisco, is the Union Savings Bank, in Oakland, at the corner of Broadway and Thirteenth street. This building is a steel-frame, stone-veneered structure, having 11 stories and a basement. It is founded upon separate concrete blocks and piers which rest upon a strong soil of mixed sand and clay. This structure was practically uninjured.

Buildings in San Francisco which rested upon foundations of sand in natural place were not injured by the shock, except where the sand was on a hillside or had opportunity to spread and flow. In such places buildings of either masonry or wood were badly shaken. Where the buildings rested upon good, hard soil, as on the hillsides or summits, practically no injury was done with the exception of the loss of chimneys and, in some buildings, of plaster. A first-class building of stone, brick, concrete, or steel frame in such situation seems absolutely proof against any earthquake of no greater severity than the one under discussion.

THE FIRE.

GENERAL DESCRIPTION.

Immediately after the first shock of the earthquake sixteen alarms of fire, from widely separated localities, were turned in to the central station. The causes of these fires were directly traceable to earthquake effects, such as the upsetting of oil lamps and oil and gasoline stoves, the contact of combustible material with lamps and gas jets, the rupturing of chimneys and flues, the scattering of chemicals, such as phosphorus, and the upsetting of boilers, furnaces, etc. It is claimed that currents of electricity did not originate any fire. Either the generators were disabled or the attendants switched off the currents.

The death of Mr. Sullivan, the chief of the fire department, which was caused by the falling of a mass of brick from a chimney while he lay ill in bed, was a most unfortunate accident, as the city was thereby deprived of his excellent knowledge and skill as a fire fighter. The fire department, although it responded promptly to the calls and was composed of brave and efficient men, with excellent apparatus, was disconcerted by the loss of its chief and paralyzed in its action by the almost complete rupture and disintegration of the water system. The city mains were so thoroughly broken that in a short time not only could no water be obtained for the extinguishment of fires, but for a number of days little water could be had for domestic use, and the people were compelled to rely on a few wells that remained available.

In private dwellings incipient fires were quickly extinguished by individual effort; but, because of the early hour, the fires which started in the great downtown business houses, factories, etc., "south of Market street," grew to alarming proportions before anyone could reach and conquer them. With the exception of the private water supplies, such as wells (see map, Pl. LVI), pumping systems, etc., possessed by a few establishments, there were no means of extinguishment. Within three hours after the earthquake nine fires were in full conflagration between "The Mission"[a] and the water front south of Market street. At first there was little or no wind to fan the flames, but the great heat soon drew in a current of air which continually increased, and, varying from one point to another, swept the flames first in this direction and then in that. By Wednesday noon the fire had consumed nearly a square mile of the city on the south side of Market street, and on the afternoon of the same day it broke across to the north side, in the vicinity of the high steel Call (Claus Spreckels), Examiner, and Chronicle buildings. Thence the fire veered with the wind, burning northward and westward through Chinatown, and joined its destructive energy with that of a separate column of fire that had swept up from the lower end of Market street and the water front. The column, driven by the wind, ate its way rapidly through the residence portion of the city, which was built of wood and hence was consumed like tinder. Three hours after the conflagration had begun a corps of dynamiters was organized, but as no such body had existed in the fire department, it was necessarily composed of volunteers and amateurs. These men fought the flames with great bravery, but with little skill, and their endeavors to arrest the progress of the fire by throwing structures down in its path were

[a] "The Mission" is a well-known locality in the city of San Francisco. It is the site of the original settlement and mission established by the Franciscan monks, and the old Mission Church still stands there (Pl. XXIII, *B*), as the fire was checked at this point just in time to save it.

futile until late on Thursday night, after a dynamite expert had been put in charge. A last stand was made in the western part of the city, at the broad and open street, Van Ness avenue. Here the dynamiters, aided by the shifting of the wind to the west, were able to stay the progress of the fire. Everything in the Mission district had been burned, except at places where the flames were checked by means of private water supplies. Although comparatively feeble, the fire continued in some parts of the desolated district until Saturday morning, April 22, when the last blaze was extinguished. The wharves and a fringe of buildings along the water front had been saved by means of engines and State fire boats drawing water from the bay.

The area of the burned district (see Pl. LVI) is 4.05 square miles, or 2,593 acres, and includes 490 blocks entirely burned and 32 blocks partially burned. These blocks were in two different classes, one being the "100-vara[a] block," and the other the "50-vara." Some structures along Mission Creek and a few residences on the summits of Telegraph, Russian, and Clay Street hills (Pl. LIV) escaped. The mint and a few other buildings were also saved by means of private water supplies.

Thus the greatest fire in the history of the world destroyed more than 4 square miles of closely built city property estimated at $500,000,000, half of which was insured; with the loss, it is believed, of about 800 human lives (though the official count is less).

San Francisco was little prepared to fight a conflagration under the existing conditions. Ever since the six devastating fires of the period from 1849 to 1852 the people had evidently relied on the excellence of the fire department (subsequently organized), the damp atmosphere, and the tradition that redwood, which composed the exterior of 90 per cent of the structures, would not burn. Dwellings were not protected against fire either from within or without, and the same may be said of most of the boarding houses and even of some of the public hotels. There were few chemical extinguishers, private water supplies, or other fire apparatus in existence. In the congested business district buildings that had ample modern means of fire prevention within, or protection against fire from without, were the exception rather than the rule. Few buildings had metal shutters, wire-glass windows, sprinkler systems (interior or exterior), or private wells, tanks, or pumps. Some buildings where these preventives were installed were saved, although surrounded by fire.

Inflammable wooden buildings—remnants of the pioneer days of 1849—were scattered through the business districts and added fuel to the flames. The magnificent high steel structures that were gutted

[a] The vara is the Spanish unit of length, and equals 33.38 inches.

by the fire owe their desolation for the most part to their environment by these inflammable buildings.

There was no dynamiting corps in the fire deparment and no adequate salt-water system for fighting fires, although the city was almost surrounded by salt water, and there were no fire boats belonging to the department, and few cisterns in the streets or squares. Most of the streets were very narrow, and many of them were lined by high wooden buildings. With the water mains and distribution system incapacitated by the earthquake, it is no wonder that the city burned; the only wonder is that it had not burned before. This result had been prophesied by insurance inspectors many months previously.

ABSTRACT OF REPORT OF ENGINEERS' COMMITTEE OF THE NATIONAL BOARD OF FIRE UNDERWRITERS.

The Coast Review, an insurance paper, gives an abstract of the report and conclusions of the engineers' committee of the National Board of Fire Underwriters. This report was published in October, 1905, many months preceding the occurrence of the great fire, and is epitomized as follows:

The area of San Francisco within the "fire limits" was 1.6 square miles. The "brick district" comprehended 0.95 square mile, and the "congested-value district" 0.49 square mile. The number of fires in the preceding nine years was moderate, but the average loss at each fire was two or three times the loss expected in cities having ordinary fire protection. The water supply was satisfactory in many respects, although the pressure (the average being 52 pounds) was too low for automatic sprinkler equipments, standpipes, etc. The fire hydrants were of an old style, and many water mains were too small. There were four water services, varying for districts of different levels. It was stated that the fire department was satisfactory in most respects, but that the building laws were not enforced thoroughly and impartially. The fire-alarm system was criticised adversely.

The "congested-value district" was bounded on the north by a mixed mercantile, warehouse, and dwelling section; on the west by a fashionable boarding-house, apartment, and residence district; on the south by a compactly built mixed district composed of dwellings and manufacturing and mercantile buildings, and on the east by the Bay of San Francisco. This district consisted of 101 blocks, containing 2,086 separate buildings, of which 2.2 per cent were fireproof, 68.3 were joisted brick, and 29.5 were frame buildings. There was only one sprinkler equipment in the district, and it was practically obsolete. Premises were generally clean and well cared for.

The "potential hazard" in the produce and commission district bounded by Battery, Washington, Drumm, and Commercial streets was said to be serious. The expert inspectors claimed to have found

"conflagration breeders." In regard to the blocks north of Market street and between Powell and Taylor streets they reported: "This section contains more serious exposures and conflagration breeders than any other equal area in the city." They reported "frequent high winds," the absence of modern protective devices generally, the "probability feature" alarmingly severe, the elements of a "conflagration hazard" present to a marked degree, and the topography unfavorable. In fact, "San Francisco has violated all underwriting traditions and precedents by not burning up; that it has not done so is largely due to the vigilance of the fire department, which can not be relied upon indefinitely to stave off the inevitable."

This report was locally regarded as very severe, and in some respects—for instance, when referring to winds, redwood lumber, and hilly topography being unfavorable—as erroneous; but, unfortunately for San Francisco, the prophecy has come true.

EXTRACT FROM A SAN FRANCISCO FIRE EXPERT'S REPORT TO THE BRITISH FIRE-PREVENTION COMMITTEE.

George J. Wellington, who was born and reared in San Francsico, and therefore can not be accused of prejudice against that city, in his report to the British fire-prevention committee of London in 1906, says, among other things:

A glance at the city from a point of eminence shortly after the temblor had subsided at once disclosed the fact that San Francisco was doomed. Columns of smoke ascending from fires at many different points made apparent a condition that no fire department in existence could cope with, on account of the impossibility of assembling sufficient apparatus at each fire to control it, and particularly on account of the fact that there was little or no pressure in the hydrants. . . . Observation for six hours from the top of a tall office building failed to illustrate anything not already known to fire experts, and previously demonstrated at Baltimore and other places. Unprotected openings of brick buildings, improperly hung and uncared-for metal-clad shutters, ineffective rolling and ordinary iron shutters, were conspicuous by their weakness. Exposed sides of hollow-tile fireproofing again cracked away; concealed piping again forced fireproofing away from steel members that it was intended to protect; metal-lath and plaster partitions again failed, and unprotected steel was warped and distorted, permitting floors to fall. Tall brick buildings with joisted interiors radiated heat to wooden cornices and window frames, which took fire. . . . In fact, everything that had been predicted by fire engineers occurred.

The bigotry of architects, the cupidity of contractors, and the penuriousness of owners have laid the metropolis of the Pacific low. The work of intelligent architects came to naught against the creations of incompetent ones. The owners of well-constructed buildings were burned out by their criminally careless neighbors. In many instances talent was not engaged on account of its ability to construct permanently and well, but rather for its shrewdness in erecting structures that would earn the greatest returns for sums invested. Competi-

tion in this respect has led to the use of inferior materials and the evasion of building laws and the underwriters' recommendations. San Francisco possesses building laws in plenty, which require enforcement rather than alteration. A valuable addition to present ordinances would be one similar to that in force in some European countries, which penalizes owners for fires that escape from their buildings, affording protection to men disposed to build well.

EFFECT OF THE LAYOUT OF THE CITY AND THE CHARACTER OF THE BUILDINGS.

San Francisco, as already stated, is divided into three great districts. Market street, the great artery of the city, 120 feet wide, runs southwestward from the bay, and divides the city into two parts—first, a level district on the south, largely filled with wooden buildings, factories, foundries, lodging houses, and the like, but around the bay extremity of the street covered to a considerable extent with buildings of brick, stone, or steel frame; second, the uneven and in its remoter parts hilly district on the north. This northerly portion is subdivided by Van Ness avenue, which separates the older residence district from the newer one on the west.

In the older section of the city, between Market street and Van Ness avenue, the streets had been established under the old Spanish system of "100-vara lots," as they are locally known, each block containing about 76,000 square feet. West of Van Ness avenue and south of Market street, in parts of the city more recently surveyed and built upon, the blocks are much larger, and—particularly along Market, Mission, and adjacent streets to the south—were built up with very long rows of buildings, many of them continuous for hundreds of feet. These blocks were so large that it was found necessary, or at least convenient, to subdivide many of them by narrow streets or alleys that permitted the ingress and egress of carts and drays. It was easy for the flames to pass across these narrow streets, and the heat was in many places so great that buildings on the opposite side of the street were ignited by the heated air without the passage of any flames.

More than 90 per cent of the buildings in San Francisco were of wooden-frame construction, and many of the new, modern, and so-called "fireproof" buildings were surrounded by frame structures of an old type, and, of course, were injured or destroyed by their combustion. The fire limits permitted these wooden structures to approach rather close to the business section; and in the congested business district at least 30 per cent of the buildings were of frame construction, some of them four or five stories in height. Outside of the congested district many business houses and almost all dwellings were frame structures, and except in the outskirts of the city

were closely built in long rows extending over entire blocks. In the business district almost every separate structure was close to its neighbors. Wide, uncovered spaces separating buildings were, as a rule, confined to the outlying suburbs. In the compactly built district of wooden structures a house every three minutes was frequently the rate of destruction from the fire during the high wind that prevailed at times.

In the congested business district about 75 per cent of the streets were 60 feet wide, and a few (about 30 per cent) were at least 80 feet wide. These streets offered very little obstruction to the passage of the flames or heated air, and it was aided by the winds that were caused largely by the conflagration.

The height limit as established by the city ordinances was 220 feet for buildings of class A, 100 feet for class B, 82 feet for class C, and 45 feet for frame buildings. Brick buildings with wooden joists were therefore allowed to be built to a height of eight stories if furnished with wire-lath and plaster ceilings, thus affording the fire admirable opportunities for destruction.

BEHAVIOR OF STRUCTURAL STEEL AND STEEL-FRAME BUILDINGS SUBJECTED TO THE EARTHQUAKE AND FIRE.

EFFECTS DUE PRIMARILY TO THE EARTHQUAKE.

INTRODUCTION.

Structural steel as a building material and as a principal stress resistant in high steel-frame buildings has greatly increased in favor since its entirely satisfactory behavior in the recent great vibrations in California; for while it possessed strength and stiffness to a satisfactory degree, it also displayed an amount of elasticity that avoided much shearing and fracture, even under the vibrations of the tallest steel-frame structures.

The behavior of structures of the various types in San Francisco and elsewhere in the area destructively affected by the earthquake was in strict accordance with the merits of their foundations, design, materials, and workmanship. The so-called fireproof buildings within the area most affected by the earthquake, and afterwards, in San Francisco, burned over, did not exceed 60 in number. Among these buildings were 8 having steel frames and hollow-tile floor arches, 29 or 30 having steel frames with reenforced-concrete floor arches, and 2 having reenforced-concrete frames—one of these of imperfect design. There were 6 unfinished buildings with steel frames, and 10 having brick walls and fireproof floor arches.

FOUNDATIONS.

It is believed that every building whose foundations were well and strongly established—upon deep piling, as the Union Ferry Building and the Merchants' Exchange; with reenforced-concrete slab, as the Call Building; upon separate concrete piers or grillages resting upon good beds having a uniform load per square foot, as the Union Savings Bank in Oakland; or upon any other type of excellent foundation—escaped injury by the earthquake to the foundations themselves, nor did the superstructure owe any damage to inefficiency in those foundations.

The central portion of California was subjected to a severe earthquake in 1868, and has, on a number of occasions since, been slightly shaken by earthquake shocks, but many architects and engineers, and the people generally, had become so accustomed to these slight movements of the earth's crust that little attention was paid to them, and, so far as the writer can learn, architects had believed that in establishing solid foundations for high steel buildings, with good anchorage and bracing, adequate to take care of extreme wind force, they had sufficiently guarded against the effects of any earthquake vibrations which might occur. As a matter of fact, the provisions thus made seem to have been ample and safe so far as any disturbance of the foundations or any lack of support of the superstructure has been detected. Notwithstanding the severe vibrations these tall buildings have been called upon to endure, they have remained plumb and very slightly damaged by the earthquake.

STRUCTURAL-STEEL FRAMES EXPOSED TO VIBRATORY MOTION.

As stated by A. O. Leuschner, secretary of the California earthquake commission, and also by Professor Omori, the distinguished seismologist of Japan, the vibratory motion in Berkeley and in San Francisco was approximately 3 inches in a horizontal direction and about 1 inch vertically, the time of the first oscillation being one second. This is understood to be the vibration on very hard soil or solid rock. Where the soil was softer and less coherent the waves became longer and the movement slower.

This vibratory motion had a tendency to move the foundation of a high building and the basement immediately in connection with it forward and back, and perhaps to move some of its columns in opposite directions, although this is not certain. At any rate, it apparently had the effect, owing to the inertia of the mass of the upper part of the building, of bringing a maximum bending moment to bear on the frame at some point between the basement and the top

of the building—to speak roughly, somewhere near the middle stories. It also seemed to have the effect of producing a horizontal shearing stress in the frame, particularly above and near the basement. The frames in these high buildings seemed to be the most severely wrenched, and the exterior walls, stairways, linings, etc., most injuriously cracked in these middle stories. For example, the magnificent eighteen-story Call Building seemed to be well braced against bending moment and shear, but the eyebars from the tenth to the sixteenth floor and the transverse wind bracing are reported to be somewhat buckled, the maximum occurring on the thirteenth floor. The braces were warped on all four sides of the building, and there was also probably some slight distortion of the steel frame from the tenth to the thirteenth floors. The exterior veneer of stone remained practically intact up to the tenth floor, above which, up to the sixteenth, there was an increasing amount of damage, some of the stone being considerably out of place. (See also p. 146.) The same thing practically can be said of the new Chronicle Building, the damage to the stonework of which can be noted by a close inspection of Pl. XXX, *B*. The earthquake proved the absolute necessity of bracing steel-frame buildings with diagonal braces, so far as the requirements of use will allow. The Mutual Savings Bank and the Shreve and Atlas high steel-frame buildings have such bracing and remained entirely plumb after the earthquake. The St. Francis Hotel and the Call Building were somewhat similarly braced and were also left in reasonably good condition.

Some architectural authorities assert that wind bracing put in liberally for an allowance of 30 pounds pressure per square foot will amply care for earthquake vibrations of an intensity equal to those of April 18, 1906. Undoubtedly many of the high steel buildings in San Francisco were designed without reference to earthquakes, but they have nobly withstood their effects, and steel frames have proved themselves entirely adapted to earthquake countries. A careful inspection of the high steel frames in San Francisco shows that they suffered comparatively little injury, and that this injury was confined to the shearing of rivets and connections, particularly in the lower stories and on the ground floors, and to some buckling of braces.

After the earthquake, bolts and rivets in the Union Trust Building were found to be loose, and some were sheared off. This damage was due apparently to faulty construction, careless workmanship, and the insertion of field bolts, in some places, instead of rivets. It was shown that the rivets, connection joints, etc., in these steel-frame structures are of vital importance, and that in order to resist earthquake vibrations they should be made as strong and effective as possible, particularly at the basement and first floor.

MASONRY WALLS AND STONEWORK.

The stone exteriors of all the high steel-frame buildings were to a greater or less extent cracked or injured under the action of the earthquake. In some places, owing probably to imperfect bond between the veneer and the steel frame, the stone veneer was displaced and the walls were bulged outward; in others, blocks were thrown to the ground and bricks or arch stones from windows and other exterior openings were dropped out of place. This disintegrating effect had its maximum in the intermediate stories between the top and the base of the building, a very good example being the Union Savings Bank in Oakland. This eleven-story steel-frame, stone-veneer structure gave opportunity for careful and comprehensive study of earthquake effects independently of fire, since it is really the only high steel-frame structure in the disturbed area which was not subjected to fire. In this building the steel frame is intact and uninjured, so far as can be ascertained. The marble veneer along the stairways and corridors and the sandstone exterior, particularly in the fourth, fifth, sixth, and seventh stories, were somewhat cracked and disturbed, indicating not only a bending but a shearing action; and the brick in the arches in some of the windows in these stories have dropped to the ground. Otherwise the building escaped damage, and it has been continuously in use since the earthquake.

The Aronson Building, at Third and Mission streets, had stone piers running from the bed up to the street level. These were badly wrenched and cracked by sheer action, and in the ninth story two courses of stone in the arches above the soffit course were badly cracked, apparently for the same reason. In the Call Building, where the stonework ends at the sidewalk level, the corner piers were not found to be cracked, but in the James Flood Building (Pls. XXXIII, *B*; XXXV, *A*), where the stonework extends to the bottom of the basement, the corner piers were cracked by earthquake action.

RELIABILITY OF STRUCTURAL STEEL.

Structural steel is a very reliable material. It is produced and also placed in position by high-class skilled labor and is not subject to the flaws which sometimes appear in concrete work as a result of poor quality of labor and inefficient inspection. Builders in this country have had much experience in the use of structural steel, and feel sure of what it will do and for what it stands. It is no longer in the experimental stage as to resistance either to earthquake tremors or, when properly fireproofed, to conflagration. Constructors in San Francisco feel that this material has safely and triumphantly passed through a most trying ordeal.

EFFECTS OF THE FIRE.

BUILDINGS.

Structural steel in the steel-frame buildings subjected to the terrific heat of the great conflagration behaved satisfactorily wherever it was properly and amply protected by any method adopted for fireproofing. In no instance that has come under the observation of the writer has the steel been injured or deformed where such fireproofing was of the proper kind and remained intact after the earthquake. Unfortunately, in many places there was practically no fireproofing whatever, or it was very poor in design or workmanship, or both, and as a consequence failed miserably. Columns were softened and buckled. Girders were softened to such a degree that they sank by their own weight, some pulling after them the walls into which they were built, others falling into the fiery furnace below, as in the Cowell Building (Pl. LI, *B*), where the fireproofing either was lacking or proved defective in the fire. In such places the columns were buckled and some of them telescoped, thus removing all support for the floors above. In other buildings where the fireproofing was fairly good and effective, as in the James Flood and the Call buildings, the structure remained ready for rehabilitation. Although all the steel girders or columns that were subjected to intense heat on account of lack of fireproofing did not fall, yet many of them were rendered unfit for further use.

Prominent among the steel structures was the eighteen-story Call Building, with dome and lantern, the architectural pride of the city. This building took fire through a tunnel leading from the power house in the rear of the building, across Stevenson street. The fire was drawn in by the draft up the 18 stories of the elevator shaft, which acted like an enormous chimney, the flames being sucked up to the topmost story with great force and rapidity. The heat, of course, became intense, and all combustible matter on the interior of the building was quickly consumed, but the fireproofing, although not perfect in design and execution, so far protected the steel frame that it remained only slightly damaged and ready for refitting. The marble lining of the walls and corridors, and the glass in the exterior and interior windows, were all destroyed, and the metal trimmings were to a considerable extent melted or ruined. But the steel frame and stone exterior, with the exception of that on some of the middle stories, remains little injured, and parts of the building are continuously in use.

In the same way the James Flood Building, one of the newest and largest steel-frame structures, excellent in design and first-class in workmanship, was fairly well fireproofed; and although gutted by

the fire, it is being rapidly refitted for store and office occupation. The Western Pacific Bank reoccupied its old quarters on the first floor of this building almost immediately after the fire.

FIREPROOFING.

GENERAL CONDITIONS.

It can be truthfully stated that perfect fireproofing of buildings in San Francisco, even in those of the newest and most modern type, was the exception and not the rule. The bent or broken columns and the distorted or disfigured steel girders in many of the burned buildings demonstrate this fact (Pl. XXVII, *B*). Wherever structural-steel framework was covered with fireproofing material of the best design, executed with conscientious, skillful workmanship, the steel remained uninjured after the fire.

The lessons taught by the great Chicago and Baltimore fires had been applied by but few of the architects of San Francisco, on account of cost restrictions insisted on by owners, and very much of the damage inflicted on these high-class structures during the conflagration is directly traceable to the imperfect fireproofing put in, or to the entire absence of fireproofing. Some of the failures were evidently and directly attributable to poor workmanship.

CONCRETE.

There are two opposing parties in the matter of fireproofing in San Francisco—those who have favored the hollow-tile system, and those who believe in concrete as the best fireproofing material. The Bekins Van and Storage Company's warehouse, the only building of considerable size in the city constructed of reenforced concrete, has already been mentioned as resisting the action of the earthquake and fire. In this building the concrete acted as a perfect fireproofing protection for the steel.

Good Portland-cement concrete has won a triumph for itself in fireproofing in San Francisco, for wherever well made and properly laid upon the steel girders or columns, it protected the metal. In very hot fires the exterior portions were disintegrated, and in some places the whole mass was cracked, necessitating removal, but the fireproofing it furnished during the conflagration was excellent. Examination showed also that it protected well against rust. The heat to which it was subjected was very great, in places common mortar being fused and ironwork in walls melted.

The steel beams and girders in the St. Francis Hotel, the Merchants' Exchange, the Mutual Savings Bank, and other similar structures that were thoroughly fireproofed with concrete endured the fire exceedingly well.

The weight of Portland-cement concrete is a drawback, and, moreover, concrete is expensive when well made and applied. Cinder concrete was well esteemed for fireproofing for floors, but the scarcity of good cinders in the city rendered its general employment impracticable.

TERRA COTTA.

As fireproofing for floors terra-cotta tiling has not given universal satisfaction. It is lighter than concrete, but the wrenching of buildings during the earthquake opened many of the joints and the mortar was destroyed—as in the Mills Building, a large ten-story steel-frame structure of the older type, having self-supporting walls. The mortar joints in the tiling were started by the earthquake, and the mortar was disintegrated by the fire, the floors being destroyed and the lower surfaces of the tiling badly spalled. The same effect was noticeable to a certain extent in the excellent Union Trust, Crocker, and James Flood buildings. In the last named the flooring was fireproofed with terra-cotta arched tiles, covered with concrete on top and finished beneath by an efficient ceiling plastered on wire lath. The fireproofing was less injured in this building than in almost any other.

Terra-cotta fireproofing of columns was in many buildings a failure, not so much on account of the nature of the material as because of its insufficiency in quantity and poor or imperfect method of application. Wooden studs were in many places put behind the terra cotta. These burned out quickly, leaving the material unsupported. Pipes and wires were run up between the column and the fireproofing, and the twisting or expansion of the pipes caused by the earthquake movement broke the protecting cover. Imperfect junctions with ceilings above or floors beneath were common. That such imperfect construction should never be adopted has been fully demonstrated in San Francisco.

Porous terra cotta has been found more satisfactory than the hard and glazed varieties. For inclosing columns, the round porous forms have proved more stable and efficient than the rectangular ones, as shown in the Spring Valley Water Company's building (Pl. XLV, *A*) and the Aronson Building (Pl. XXVII, *B*).

PLASTER AND METAL WORK.

Common plaster on wire mesh, metal lath, or expanded metal was very generally used for the fireproofing of columns, partitions, and the like, on account of its cheapness, but was a failure when subjected to a hot fire, as proved in the Hotel Fairmount (Pl. XXXIV), the Hotel Hamilton, and several other buildings. This failure was much more noticeable where only a single wrapping or thickness of the wire

mesh, etc., was used than with the double wrapping. But even the latter proved to be too weak and disintegrable to pass successfully through a severe earthquake or a fire and a strong stream of water from a fire hose. The plaster quickly cracks and falls away from the metal. No doubt these materials will be used in the future by owners demanding cheapness of construction, but they will satisfy the requirements only in cases of mild exposure. Good gravel concrete in place of the plaster, if of considerable thickness, has been found to give better results.

The failure of the plaster and metal method and some other methods of fireproofing in San Francisco is directly traceable to the commands of owners to their architects to cheapen as far as practicable the fireproofing and the construction generally, in order to receive greater interest on their investments. Much of this cheapening has been done in spite of the protests of the designer, and it is in an entirely wrong direction; for rates of insurance are largely reduced with improvements in fireproofing, and as the cost of the steel frame and its proper fireproofing seldom exceeds 27 per cent of the cost of the building, it seems wise to protect the other 73 per cent with adequate materials.

BRICKWORK.

In some buildings in San Francisco, brick laid in rich Portland-cement mortar has been found to be an excellent fireproof covering; but it is objectionable on account of the bulkiness of the brick and the rusting of the steel, as in basement stories. Good brick withstood the severe fire well, and where laid in rich cement afforded a strong fireproof wall or pier. At least 4 inches of brickwork was found necessary, and a layer of concrete 3 inches in thickness between that and the steel was a great improvement and served well to protect the steel from rust. But this method will probably not be followed in general, on account of weight, bulk, and expense. Hollow brick and tiling were efficient also when properly and liberally used, porous tiles proving to be the better.

The well-known Palace Hotel was built about thirty years ago, a few years after the earthquake of 1868, and before the introduction of steel-frame structures and concrete steel. It was intended to be earthquake proof as well as fireproof, and was built with very heavy walls of brick, most of them being 2 feet or more in thickness, laid in cement mortar, and strongly braced by many cross and partition walls. In the brickwork, at every 3 or 4 feet in height, were laid bands of iron, riveted together at their ends and crossings. This building, although of the old type, successfully endured the great earthquake, its walls being practically uninjured (Pl. XXX, *B*);

and although gutted by the fire, which gained access through the unprotected windows and wooden casings, was so strong on its foundations that very vigorous blasting operations were required to throw down its walls.

REENFORCED CONCRETE.

There was in San Francisco at the time of the earthquake only one building of considerable size constructed of reenforced concrete. This fact was due to the opposition of certain labor unions to the use of this material in place of brick and stone.

The building referred to is that of the Bekins Van and Storage Company, at 190 West Mission street (Pl. XXVII, *A*). This building had outside walls of brick, but was massively constructed on the interior with columns, beams, and floors of reenforced concrete. It was originally intended to carry it to a height of four stories, but on account of the earthquake, which occurred during construction, the building was finished to include only the second story. At the time of the fire the permanent doors of iron were not in place, and the fire gained access to the front or south room, where very slight damage was inflicted. The entire main interior and the goods stored therein were unharmed, and the building has been in continuous use since completion. The brick building adjoining, however, was badly injured by the earthquake and was afterwards burned.

LESSONS FROM THE VARIOUS TYPES OF BUILDINGS.

Great destructive earthquakes have seldom occurred twice in the same locality during centuries of time, but, so far as man knows, one may occur at any time anywhere on the earth's surface. On the other hand, destructive conflagrations in cities have happened many times, but most of them might have been avoided by wise and adequate provision for fire prevention, protection, and extinguishment.

In San Francisco the earthquake could not have been averted, but its disastrous effects on structures could have been prevented by the use of proper materials correctly applied in the execution of skillful and scientific designs, carried out by good conscientious workmen under honest and able supervision. The city's official inspection has usually been very inefficient.

The buildings in California that were ruined or badly injured by the last earthquake may be divided into four classes:

The first class comprises buildings of a public character, such as city halls (Pl. XXXI), court-houses (Pl. XXXIX, *A*), asylums, public schoolhouses, etc., which were badly desibned and constructed or for the construction of which insufficient funds had been voted, so that the materials and workmanship, under imperfect inspection, or

worse, were of very poor quality. In contrast to such construction were the United States Government buildings—the mint and the appraisers' (or customs) building (Pl. XXVIII, *A*), in San Francisco, and the post-office building in Oakland—all of which were either entirely uninjured or very slightly injured by the earthquake. These buildings were well designed and constructed with the best materials and workmanship, upon foundations that had been tested and found strong and satisfactory. The results to both of these classes of buildings were fully to be expected.

As a second class of buildings that suffered badly may be grouped those of the oldest type of wooden structure in San Francisco, lightly resting upon slim wooden underpinning, which stood upon soft and unstable soil or loose, unconsolidated sand. Such houses went down at the first shock, as one would naturally expect. In contrast to these flimsy structures are the thousands of more substantially constructed wooden buildings that still stand intact, except as to chimneys and some plastering, all over the unburned part of the city. These structures were built fairly well and upon stable foundations; and the writer believes from his personal observation that no well-founded and well-constructed building of wood in San Francisco was injured to a greater degree than those just mentioned. In a country subject to earthquakes a strongly framed and well-founded wooden house, not exceeding three stories in height, with nondisintegrating plaster and finish, light tile chimneys, and ample fire prevention and protection, would seem to be the ideal type of residence structure.

Experience shows that buildings constructed with exterior brick walls laid in common mortar, with timber columns and girders, tied and braced little or not at all, constitute a third class of buildings which are nonresistant to a severe earthquake, particularly if they are erected upon a poor foundation. Even if the girders and columns are of metal, they are pulled apart, and the walls fall inward or outward during the shock. Only rich Portland cement, laid with wetted brick, and strong joists, ties, and anchorage, endured the stress.

The behavior of the high steel-frame office buildings, which constitute the fourth class, has shown that in order to resist perfectly the bending moments and shears induced by the swaying due to the earthquake movement, such buildings should be stiffened in their joints and connections by the best riveting combinations, and knee and other bracing, particularly at or near the ground floor. This requirement is of the utmost importance, and so also is the one that the swaying referred to should be diminished by the liberal introduction of diagonal and wind bracing throughout. The proper bracing in the lower stories has in some buildings been omitted, on the demand of

owner or lessee, to afford more glass or light space, but such design has a weakening effect, and should be discouraged. The Marston Building, on Kearney street, is an object lesson in this respect. On the other hand, the Whittell Building, on Geary street, near Union square, is commended for its deep plate girders and heavy steel generally. It stood well, and no rivets were sheared. Columns, exterior and interior, in steel-frame buildings, should in future be put in more liberally on the first and second stories, and the strongest joints and connections should be adopted in order to resist the bending and shearing. These improvements will greatly stiffen the steel frame, and prevent the cracking of the walls. The Kohl Building, thus stiffened by lattice girders on all floors, was uninjured in its exterior stonework and brickwork, although built upon the edge of the made ground along the old shore line. With such strengthening the high steel structures will safely endure an earthquake of even greater severity than that of April 18, 1906. This kind of building has proved its worth and reliability, and minor improvements, as advocated, will produce an enduring structure.

In a fifth class are to be placed, but not as failures, concrete and reenforced-concrete structures. These have become popular with a large number of designers in San Francisco, on account of the strength claimed for them, and on account of the indestructibility, facility of construction, and fire and rust protection that their materials afford. Unfortunately for San Francisco, there were very few structures of concrete or reenforced concrete in the city at the time of her great trial; but these few behaved well during both the earthquake and the resulting fire. Therefore, although such structures are admittedly new and comparatively experimental on the Pacific coast, the confidence reposed in them has already led to the designing and construction of a number of large buildings of this type for public or business purposes. At present the sentiment is to limit them to a height of six or eight stories, on account of their experimental character and because of the fear that greater height would permit a reversal of stress, due to earthquake and wind force in their reenforced girders. It is agreed that the columns should be reenforced with steel and braced together wherever possible; that the girders should be similarly reenforced for tension and shear, and made, so far as practicable, continuous over the columns; and also that the joints and connections should be strongly stiffened and the curtain walls strengthened by a reenforcement.

Mill construction with brick will undoubtedly be utilized in many buildings for a considerable time to come, but the lesson has been taught that the materials used should be first-class pressed brick, well wetted, and cement mortar, and that all parts should be thoroughly

tied and anchored together. San Francisco's experience has proved that this rule is a most important one to follow in all brick and stone construction, and its neglect in the past has resulted in much loss and ruin.

FIRE-FIGHTING APPARATUS AND FIRE-RESISTING MATERIALS.

The damage inflicted on San Francisco from the direct and immediate effects of the earthquake was relatively small, being estimated at only 3 to 10 per cent of the total loss; but a subsequent and indirect effect was to paralyze the water supply and its distributing system, start a great conflagration and render impossible its extinguishment with the means at hand, cause the death of at least 600 human beings, burn approximately $500,000,000 worth of property, render homeless and miserable 200,000 people, and inflict remoter damages to business, commerce, and labor, only to be estimated in the future. Inasmuch as it can be plainly seen, by looking backward, that nearly all of this destruction and suffering might have been prevented by wise foresight and provision, it is felt that a warning should be sent to all the cities in the world. Any city that disregards this warning will be guilty of a great crime.

San Francisco should have had separate and ample water mains entering the city on several independent lines from different sources of supply, and numerous distributing reservoirs on the hills in various parts of the city, always well filled, independent and yet with a distributing system meshing the entire area, with its pipes so joined or valved that they could be separated or united as desired. There should have been in that city, almost surrounded by salt water, a separate system of flexible salt-water mains for fire and sewer purposes, and numerous large cisterns in her streets, laid in reenforced concrete, with somewhat flexible lining and pipes. These cisterns, only a few blocks apart, should have been filled at all times with salt water. There should have been many wide streets—like Van Ness avenue, where the fire was finally checked—and many large squares, the city being thus divided into numerous fire districts. The fire department should have included a dynamiting corps of experienced fire fighters, and a number of fire boats always ready along the water front and among the shipping. None of these things did San Francisco have. With these means available, probably this story of the greatest fire in history would never have been written.

Of a building's entire fire risk, that from fire within the building is estimated, on the average, at 40 per cent, the other 60 per cent of the risk being from exterior fires. This risk for interior fires should

be reduced to a minimum by ample provision for fire prevention. As far as practicable, combustible material should be eliminated. Several of the fine so-called fireproof buildings in San Francisco were injured chiefly by the burning of their wooden trim, floors, doors, office furniture, papers, books, carpets, rugs, etc. Wooden floors have proved to be dangerous and objectionable; but in some places non-combustible wood may be used for them and for the interior trim, as, for example, where the heat could never be very great. Metal trim, doors, windows, sash, and casings, together with plate glass, or, better, wire glass, may confine a fire to a single room, preventing a general combustion. Adequate fire-extinguishing apparatus—such as fire hose, always connected with good water pressure, wells with automatic pumps, and tanks in the basement or upon the roof, with pipe connections—was lacking in nearly all of San Francisco's buildings, even in those of the highest class. In the California Electric Company's building the standpipes, with attached hose, the well, pump, and tank in the basement, and the roof tank, together with the metal sash and the wire-glass windows, proved the value of such a private system, saving that property from the hot fire around it, though every adjacent structure was burned. As this building was not fireproof, the value of the fire-extinguishing system can be well understood, and had all the large establishments been equally well equipped the conflagration would have been quickly checked and a vast amount of property saved. Automatic sprinklers connected with the above-mentioned plant will afford excellent fire protection within and will greatly reduce insurance rates.

While the fire danger from exterior fires to a given building is ordinarily estimated at 60 per cent, this risk practically becomes 100 per cent, of course, in a great conflagration. In San Francisco little protection from exterior fires had been adopted. There were few metal shutters or steel roller shutters, and most of those were of imperfect design, proving unsatisfactory when tested. The openings in walls were fatal points of weakness in all the great buildings. Wire-glass windows, though few in number, behaved well, but wooden instead of metal sashes were great sources of fiery contagion. Metal covering over wooden doors and window frames was generally inefficient. Ordinary glass was quickly cracked by heat from the exterior; the sashes took fire and the flames rushed in through the openings, consuming all combustible material within. Many of the best buildings were gutted in this manner. Had they been furnished with metallic shutters of the best design, with wire glass in metal sashes, and with cornice and other exterior sprinklers, supplied by a private water plant, they certainly might have been saved. Thus the employees of the United States mint (Pl. XXXVIII), with a

scanty private supply of water, made a desperate and gallant fight from the roof of the building and within, and saved it, little injured.

As most metallic shutters rapidly deteriorate with time, rust, and weather, and often become jammed so that they will not close, many architects prefer wire glass in hollow metallic sash and window sprinklers. This combination has proved effective.

San Francisco's experience indicates that wells and elevator shafts, running up through many stories, should be guarded by brick or reenforced-concrete walls, fitted with double metal rolling doors, bolted to the walls to allow for expansion, or with automatic sliding doors and wire-glass partitions. There was little or no provision for cutting off the draft of air that will ascend through such a shaft during a fire, and great destruction resulted in consequence. The Call Building took fire from the power house behind it, on the other side of Stevenson street, the heat being drawn through the tunnel to the elevator shaft, up which it rushed with the fierce draft given by the 18 stories, breaking glass and burning doors, furniture, trimmings, and office contents. The Telephone Building, on Bush street (Pl. XLI, *A*), met a similar fate, being consumed from within. This new structure was claimed to have the best fire protection in the city.

The importance and value of real protection will be appreciated when it is stated that a third-class building with a complete fire-prevention plant is insured for less than a first-class one that does not have it. This fact should be understood by all owners. Moreover, all parts of an establishment should be equally protected, for the fire may begin anywhere. The new Telephone Building was burned owing to the nonobservance of this rule, catching fire through the unprotected wooden back door of the basement. The structure was fitted with "tin-clad shutters" and wire glass on the side and rear openings and with steel rolling shutters in front. The fire broke through the rear wooden door into two well shafts and a corridor and, rushing upward, consumed every floor. The building was destroyed by a fire that entered through a single unprotected opening. The tin-clad shutters were destroyed and much of the wire glass was melted or broken by the hot fire. The rolling shutters in front still hung, but were bent so that the windows were exposed.

Concrete floors with metallic-mesh reenforcement are strongly recommended for strength and fireproof character. Noncombustible wooden floors, doors, and trim were installed in a few buildings, and under ordinary conditions would probably have limited the destruction to "one-room fires," but the heat was so high, and in general the bulk of papers, books, and furniture so great, that all were consumed. A noninflammable substitute for woodwork and trim generally is greatly to be desired.

Double windows of wire glass in hollow metallic frames are recommended, or where such material would be objectionable by cutting off the view, double plate glass is considered next best. Interior doors should be of metal, or at any rate metal covered, in fireproof buildings, and the light for corridors and halls should come through wire glass. As the installation of wire glass, metallic rolling shutters, and metal sash involves only a small percentage of the cost of the building, and as these materials have proved to be of such excellent service as fire protection when of the best quality and workmanship, a wise economy demands their use in every important fireproof building.

Capitalists and owners must understand that perfect fire protection for structural steel is necessarily expensive. Any so-called fireproofing that is cheap and flimsy is a delusion and will not serve. The application of an effective method insures permanence of the structure and at the same time greatly reduces the rates of insurance. Steel columns may be well fireproofed by surrounding them with the best quality of stone or cinder concrete 4 inches in thickness, or by 3 inches of either when hollow tiling is put on the exterior.

A 3-inch porous terra-cotta tiling, wrapped on the outside with wire, and with metal mesh used around the bed course of the column, has proved efficient. The mortar of the tiles should contain a large proportion of cement, and the tiles should be strongly anchored to the columns to prevent their falling away in earthquake or fire and so leaving the steel exposed.

In the great fire, decorations, trim, inflammable oil paints and varnishes, in office buildings, aided materially in spreading the flames. A noninflammable water-color paint that will endure washing has been recommended.

Fire walls of brick, extending above the roofs of buildings, were effective in resisting the spread of the fire; but the support derived from metal bands and anchors was neglected in many such walls, as in much other masonry in San Francisco; a large number of them fell, therefore, during both the earthquake and the fire, particularly those laid in common mortar. This was also a common fate of unsupported gables and towers. Walls that were well anchored, as in the Union Trust Building, remained in perfect condition.

Cast-iron columns in some buildings endured the earthquake and the fire fairly well, but undoubtedly would have been broken or shattered had cold water been thrown upon them in the midst of the great heat. They should no longer be used, for at present they cost more than steel for an equal factor of safety, and their connections are clumsy and weak.

Structures made of concrete blocks were as a rule greatly damaged

or even ruined by the earthquake, owing to imperfect anchorage and failure to cohere at their joints (Pl. XVII, *A*).

Granite, sandstone, and marble were badly cracked and spalled by the fire, much of the marble crumbling to powder. The granite piers in the front of the Hobart Building were nearly all chipped away, and they are now reenforced by new temporary supports.

Chemical fire extinguishers were effectively used immediately after the earthquake in some of the uptown residences, thereby preventing an increase in the number of fire centers at the beginning of the conflagration. It is possible that numerous chemical engines and locally installed chemical extinguishing plants in the downtown districts might have greatly limited the spread of the flames, despite the dearth of water.

FINAL CONCLUSIONS.

EARTHQUAKE PROTECTION.

A proper foundation, stable and firm, is of vital importance, and particularly on soft, marshy, or made ground (Pls. XLIII, *B*; XLIV, *A*). Anchoring, bonding, and tying should be practiced with exactness in all masonry. Steel framing should be made heavier rather than lighter, and joints, connections, bracing, and flooring should be strongly united. Girders and columns should be made very stiff and, where practicable, continuous.

FIRE PROTECTION.

The lessons taught by the great fires of Boston, Chicago, and Baltimore have been verified by San Francisco's experience.

Fireproofing should be of the most perfect type, and no reasonable expense should be spared in its installation.

Roofs, roof appurtenances, and skylights should be given ample protection against fires from without. A great excess of fire hose and apparatus, beyond ordinary needs, should be available. A strong bond for fireproof tiling, etc., for both girder and column protection, is essential. Protection for front windows, as well as for side and rear ones, is of vital importance. Good protection for steel frames and steel roof trusses in attics or other exposed or unusual places should be provided. Liberal use should be made of fire retardant in windows, doors, transoms, etc. Wise and liberal use of concrete and reenforced concrete for girder and column fireproofing has proved its saving quality. Interior fire protection and prevention by wells, pumps, sprinklers, and water tanks vastly lessen fire risk.

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Young Building. *See* Ætna Building.

CLASSIFICATION OF THE PUBLICATIONS OF THE UNITED STATES GEOLOGICAL SURVEY.

[Bulletin No. 324.]

The publications of the United States Geological Survey consist of (1) Annual Reports, (2) Monographs, (3) Professional Papers, (4) Bulletins, (5) Mineral Resources, (6) Water-Supply and Irrigation Papers, (7) Topographic Atlas of United States—folios and separate sheets thereof, (8) Geologic Atlas of United States—folios thereof. The classes numbered 2, 7, and 8 are sold at cost of publication; the others are distributed free. A circular giving complete lists can be had on application.

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2. A certain number are delivered to Senators and Representatives in Congress for distribution.

3. Other copies are deposited with the Superintendent of Documents, Washington, D. C., from whom they can be had at prices slightly above cost.

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SERIES R, STRUCTURAL MATERIALS.

B 324. The San Francisco earthquake and fire of April 18, 1906, and their effects on structures and structural materials; reports by G. K. Gilbert, R. I. Humphrey, J. S. Sewell, and Frank Soulé, with preface by J. A. Holmes. 1907. 170 pp., 57 pls.

Correspondence should be addressed to

THE DIRECTOR,
UNITED STATES GEOLOGICAL SURVEY,
WASHINGTON, D. C.

AUGUST, 1907.

O

A. ROAD CROSSING FAULT TRACE NEAR POINT REYES STATION.

Looking southwest. Offset, 20 feet. Photograph by G. K. Gilbert.

B. FENCE PARTED BY EARTHQUAKE FAULT.

The fault trace or fracture accompanying the earthquake is inconspicuous, although the horizontal displacement is considerable. Photograph by G. K. Gilbert.

EARTHQUAKE EFFECTS ALONG THE FAULT TRACE.

REDWOOD TREE 6 FEET IN DIAMETER ON LINE OF FAULT SOUTH OF FORT ROSS.

The tree was split to a height of 35 feet, although the horizontal displacement was slight. The opening is wedge-shaped at the base, running from a width of 8 inches on the side shown to a fine crack on the farther side. Photograph by Richard L. Humphrey.

A

B

THE FAULT TRACE NEAR POINT REYES STATION.

A, Looking northwest; *B*, Looking southeast. Photographs by G. K. Gilbert.

A. SECONDARY CRACKS, SHORE OF BOLINAS LAGOON.

Photograph by G. K. Gilbert.

B. SECONDARY CRACKS, WITH SETTLING, BOLINAS.

Photograph by G. K. Gilbert.

RESULTS OF EARTH FLOW, NINTH STREET, SAN FRANCISCO.

Photograph by G. K. Gilbert.

A. SETTLING (5 FEET) ON DORE STREET, BETWEEN BRYANT AND BRANNAN STREETS, SAN FRANCISCO.

Photograph by Richard L. Humphrey.

B. BUCKLING CAUSED BY EARTH FLOW, HOWARD STREET, SAN FRANCISCO.

Photograph by G. K. Gilbert.

EARTHQUAKE EFFECTS ON MADE GROUND.

A. EARTHQUAKE RIDGES ON TIDAL FLAT, TOMALES BAY.
Photograph by G. K. Gilbert.

B. SLIPPING OF ALLUVIAL SOIL TOWARD SALINAS RIVER.
Grain field adjoining road along river between Spreckels's sugar mill and Salinas. Photograph by A. C. Lawson.

A

B

DAMAGE TO PILARCITOS 30-INCH PIPE LINE BY EARTHQUAKE.

A, Offset; *B*, Telescoping. Photographs submitted by Frank Soulé.

A. COLLAPSED PILARCITOS 30-INCH WROUGHT-IRON PIPE LINE, NEAR TRESTLE CROSSING THE FAULT.

The slip produced a compression on the pipe line which buckled it, thereby throwing down the trestle support. The consequent parting of the pipe line suddenly released the water from the pipe, causing a vacuum which brought about the collapse. Photograph by Richard L. Humphrey.

B. HOUSE ON LINE OF FAULT, TORN ASUNDER BY EARTHQUAKE.

Near Wrights Station, on Southern Pacific Railroad. Photograph by Richard L. Humphrey.

A. RACKING AND SPALLING OF CONCRETE PIER DUE TO EARTHQUAKE.

Near south abutment of Southern Pacific Railroad bridge over Pajaro River. Photograph by Richard L. Humphrey.

B. ENDURANCE OF CONCRETE DAM NEAR FAULT TRACE, AT CRYSTAL SPRINGS LAKE, SAN MATEO.

Photograph by Richard L. Humphrey.

A. EFFECT OF EARTHQUAKE ON THE END AND THE INSUFFICIENTLY BRACED CENTRAL PORTION OF A BRICK BUILDING, SPRECKELS'S SUGAR MILL, ABOUT 4 MILES SOUTH OF SALINAS.

Note the stripping of brick pilasters from steel columns. Photograph by Richard L. Humphrey.

B. EARTHQUAKE WRECK OF NEW HALL OF JUSTICE, SAN JOSE, BUILT ON ALLUVIAL SOIL.

Wreck due to poor quality of stonework and unnecessarily massive construction. Photograph by Frank Soulé.

A. COMPARATIVE EARTHQUAKE ENDURANCE OF DISSIMILAR STRUCTURES, AGNEW INSANE ASYLUM, NEAR SAN JOSE.

Tanks on steel trestle, undamaged, and circular brick stack, collapsed. Photograph by Richard L. Humphrey.

B. EARTHQUAKE EFFECT, HIGH SCHOOL BUILDING, SAN JOSE.

Photograph submitted by Frank Soulé.

A. COMPARATIVE BEHAVIOR OF REENFORCED CONCRETE AND BRICKWORK UNDER EARTHQUAKE VIBRATION, MUSEUM, LELAND STANFORD JUNIOR UNIVERSITY.

The central portion, of reenforced concrete, was undamaged, but the brick wings collapsed. Photograph by Richard L. Humphrey.

B. COMPLETE WRECK BY EARTHQUAKE. COURT-HOUSE AND HALL OF RECORDS, SANTA ROSA.

Wreck due to light wooden framing, insufficient bracing, and poor mortar. Photograph submitted by Richard L. Humphrey.

A. UNDAMAGED STEEL FRAMEWORK SUPPORTING DOME OF LIBRARY.

B. COLLAPSE OF BRICK WALLS, CAUSING DESTRUCTION OF STEEL SKELETON DOME OF GYMNASIUM.

ENDURANCE OF STEEL FRAMEWORK AS AFFECTED BY METHOD OF SUPPORT, LELAND STANFORD JUNIOR UNIVERSITY.

Photographs by Richard L. Humphrey.

A

B

MEMORIAL ARCH, LELAND STANFORD JUNIOR UNIVERSITY.

A, Before the earthquake (photograph submitted by Richard L. Humphrey); *B*, Earthquake effect (photograph by Richard L. Humphrey). The beams designed to stiffen the walls were not tied to them and helped to batter them down when the shock came.

A. COLLAPSE DUE TO LACK OF TIE BETWEEN WALLS AND FRAME, THIELE BUILDING (CEMENT BLOCK), PALO ALTO.

Photograph by Richard L. Humphrey.

B. COLLAPSED TOWER AND GENERAL EARTHQUAKE WRECKAGE, MEMORIAL CHURCH, LELAND STANFORD JUNIOR UNIVERSITY.

Photograph by Richard L. Humphrey.

A. EARTHQUAKE DAMAGE DUE TO LACK OF TIE AND BRACING, GEOLOGICAL DEPARTMENT, LELAND STANFORD JUNIOR UNIVERSITY.

Photograph by Richard L. Humphrey.

B. EARTHQUAKE EFFECT ON ARCHES, LELAND STANFORD JUNIOR UNIVERSITY.

Spalling of caps and movement of upper part of columns. Photograph by Richard L. Humphrey.

A. ENDURANCE OF WALLS TIED TOGETHER WITH STEEL RODS, LEE BROTHERS' WAREHOUSE, SANTA ROSA.

Slightly damaged at cornice. The few blocks which were thrown down by the earthquake were replaced previous to the taking of the photograph.

B. WALL THROWN DOWN BY EARTHQUAKE VIBRATIONS OF ROOF TRUSSES WHICH WERE NOT TIED TO WALL, VANDERVOORT BROTHERS' LIVERY, PALO ALTO.

EARTHQUAKE EFFECTS ON CEMENT-BLOCK WALLS.

Photographs by Richard L. Humphrey.

A. LOOSENING OF ARCH STONES AND SPALLING OF COLUMNS BY EARTHQUAKE, FRANCIS SCOTT KEY MONUMENT, GOLDEN GATE PARK, SAN FRANCISCO.

Photograph by Richard L. Humphrey.

B. UNDAMAGED REENFORCED-CONCRETE STRUCTURE AT MILLS COLLEGE, NEAR OAKLAND.

Bell tower, within a few feet of a brick building that was badly racked by the earthquake.
Photograph by Richard L. Humphrey.

A. RACKING OF NEWLY CONSTRUCTED BUILDING, SYNAGOGUE, GEARY AND FILLMORE STREETS, SAN FRANCISCO.

Note the separation of the brick veneer from the backing; also the racking of the wall at the corner. Photograph by John Stephen Sewell.

B. GOOD EARTHQUAKE ENDURANCE OF BUTTRESSED WALLS, SYNAGOGUE EMANUEL, SAN FRANCISCO.

Photograph submitted by Richard L. Humphrey.

A. X CRACKS IN BRICKWORK, CAUSED BY ROCKING, HOUSE IN SAN FRANCISCO.

Photograph submitted by Richard L. Humphrey.

B. SLIP OF FOUNDATION OF CYCLORAMA, STRAWBERRY HILL, GOLDEN GATE PARK, SAN FRANCISCO, CAUSING COLLAPSE OF THE STRUCTURE.

Photograph by Richard L. Humphrey.

A. EARTHQUAKE EFFECT ON STRUCTURE OF REENFORCED CONCRETE OF POOR QUALITY.

Cyclorama, Strawberry Hill, Golden Gate Park, San Francisco. Photograph by Richard L. Humphrey.

B. EFFECT OF EARTHQUAKE ON ADJACENT BUILDINGS OF DISSIMILAR TYPE AND CONSTRUCTION.

Old Mission Dolores, San Francisco, undamaged. Tower of new church adjoining was so badly damaged that it had to be taken down. Photograph by Richard L. Humphrey.

A. FAILURE OF CAST-IRON SHELL OF CONCRETE-FILLED CAST-IRON COLUMN BY FIRE, ACADEMY OF SCIENCES BUILDING, SAN FRANCISCO.

The concrete core supports the load. Note also the effect of the earthquake on the brick wall in the rear. Photograph by Richard L. Humphrey.

B. SPALLED GRANITE, MARKET STREET ENTRANCE OF ÆTNA BUILDING, SAN FRANCISCO.

Photograph by Richard L. Humphrey.

A. SUBSIDENCE OF STREET IN FRONT OF ÆTNA BUILDING, SAN FRANCISCO.

Photograph by John Stephen Sewell.

B. FIRE ENDURANCE OF CONCRETE, ANNEX OF ACADEMY OF SCIENCES BUILDING, SAN FRANCISCO.

Reenforced-concrete floors and concrete-filled cast-iron columns with plaster covering. Photograph by Richard L. Humphrey.

A. BUCKLED COLUMNS AND COLLAPSED FLOOR PANEL, BULLOCK & JONES BUILDING, SAN FRANCISCO.

Photograph by John Stephen Sewell.

B. INCIPIENT FAILURE OF NAKED CAST-IRON COLUMN IN CITY HALL, SAN FRANCISCO.

Ceiling on the point of falling. Photograph by John Stephen Sewell.

A. EARTHQUAKE ENDURANCE OF REENFORCED-CONCRETE BUILDING, BEKINS VAN AND STORAGE COMPANY'S WAREHOUSE, SAN FRANCISCO, UNDER CONSTRUCTION.

The only building of pure reenforced-concrete type in the city. The brick walls composing the shell of the building were cracked, but the reenforced-concrete floors and columns were uninjured. Photograph by Richard L. Humphrey.

B. FAILURE OF TERRA-COTTA COLUMN COVERINGS, RESULTING IN BUCKLED COLUMNS; ENDURANCE OF CINDER-CONCRETE FLOORS; CENTER OF GROUND FLOOR, ARONSON BUILDING, SAN FRANCISCO.

Photograph by Richard L. Humphrey.

A. EARTHQUAKE ENDURANCE OF A WELL-CONSTRUCTED BRICK BUILDING: APPRAISERS' WAREHOUSE, SAN FRANCISCO.

The walls were built with full-header courses and show only a few slight cracks, although the building was located on alluvial soil. Photograph by Richard L. Humphrey.

B. FAILURE OF ORNAMENTAL TERRA COTTA, CROCKER ESTATE BUILDING, SAN FRANCISCO.

This terra cotta failed, though solidly filled with brick mortar. The damage shown was probably due to fire, although damage of this kind was caused by both earthquake and fire. Photograph by John Stephen Sewell.

A. EARTHQUAKE CRACKS IN WALL OF VAULT, CALIFORNIA CASKET COMPANY'S BUILDING, SAN FRANCISCO.

Photograph by Richard L. Humphrey.

B. COLLAPSE OF FLOOR PANEL, CAUSED BY LOAD FALLING FROM A FLOOR ABOVE, THIRD FLOOR OF ÆTNA BUILDING, SAN FRANCISCO.

The *failure of the upper floor* was due to the softening by heat of reenforcing steel bands. Photographs by Richard L. Humphrey.

A. EARTHQUAKE DAMAGE MINIMIZED BY SPECIAL CONSTRUCTION, DEWEY MONUMENT, SAN FRANCISCO.

B. X CRACKS IN WALLS, DUE TO ROCKING OF BUILDING BY EARTHQUAKE, CHRONICLE BUILDING AND ANNEX, SAN FRANCISCO, LOOKING EAST.

RUIN OF THE $7,000,000 CITY HALL, SAN FRANCISCO, BY EARTHQUAKE AND FIRE.

Photograph submitted by Frank Soulé.

A

B

COMPLETE FAILURE OF SLOW-BURNING WOOD CONSTRUCTION, THE EMPORIUM, SAN FRANCISCO.

A large department store. *A*, Interior (photograph by John Stephen Sewell); *B*, Exterior (photograph by Richard L. Humphrey).

A. BEHAVIOR OF STEEL FRAME, BUTLER BUILDING (INCOMPLETE), AT THE SOUTHWEST CORNER OF GEARY AND STOCKTON STREETS, SAN FRANCISCO.

Walls taken down in places because of earthquake damage, although damage to steel

B. EARTHQUAKE DAMAGE TO STONE PIERS, JAMES FLOOD BUILDING, SAN FRANCISCO.

Photograph by John Stephen Sewell.

A

B

C

BUCKLING OF COLUMNS DUE TO FAILURE OF PLASTERED METAL-LATH FIREPROOFING, FAIRMOUNT HOTEL, SAN FRANCISCO.

The method of fireproofing was to inclose the column between the metal lath forming the partitions. Photographs by Richard L. Humphrey.

A. INCIPIENT BUCKLING OF COLUMNS FROM HEAT, FIRST STORY, JAMES FLOOD BUILDING, SAN FRANCISCO.

The brick filling probably saved the columns from fatal buckling or collapse. Photograph by John Stephen Sewell.

B. FAILURE OF SUSPENDED CEILING, HALL OF JUSTICE, SAN FRANCISCO.

Photograph by Richard L. Humphrey.

A. GRANITE COLUMNS SPALLED BY FIRE, HOBART BUILDING, SAN FRANCISCO.

Photograph by Richard L. Humphrey

B. BUCKLING OF COLUMNS DUE TO FAILURE OF WIRE-MESH-AND-PLASTER FIREPROOFING, HOTEL HAMILTON, SAN FRANCISCO.

The fireproofing on either side shows the general condition in which it was left by the fire. It was stripped away from the column just before the photograph was taken in order to show the buckling. Photograph by A. L. A. Himmelwright.

A. STONEWORK SPALLED BY FIRE, HIBERNIA SAVINGS AND LOAN SOCIETY'S BUILDING, SAN FRANCISCO.

Photograph by Richard L. Humphrey.

B. EARTHQUAKE DAMAGE, JACKSON BREWING COMPANY'S BUILDING, SAN FRANCISCO.

Light walls, badly bonded and laid up with poor lime mortar, and flimsily constructed steel work. Photograph by Richard L. Humphrey.

A. GOOD EARTHQUAKE ENDURANCE OF A BUILDING OF THE MONUMENTAL TYPE: UNITED STATES MINT, SAN FRANCISCO.

Showing only slight damage to brick stack, probably due to earthquake. Photograph by John Stephen Sewell.

B. SPALLING OF STONEWORK BY FIRE, NORTHWEST FRONT OF UNITED STATES MINT.

Photograph by Richard L. Humphrey.

A. WRECKED TOWER AND SPALLED STONEWORK, HALL OF JUSTICE, SAN FRANCISCO.

Photograph by John Stephen Sewell.

B. COMPLETE WRECK BY EARTHQUAKE, DUE TO POOR DESIGN, MAJESTIC THEATER, SAN FRANCISCO.

Photograph by Richard L. Humphrey.

A. SPALLING OF ENAMELED BRICK IN LIGHT WELL, AND FAILURE OF FIREPROOFING OF WINDOW-FRAME SEPARATORS, MERCHANTS' EXCHANGE BUILDING, SAN FRANCISCO.

Photograph by Richard L. Humphrey.

B. BUCKLING OF BASEMENT COLUMN DUE TO FAILURE OF TERRA-COTTA COVERING IN FIRE, MILLS BUILDING, SAN FRANCISCO.

Photograph by Richard L. Humphrey.

A. ENDURANCE OF A WELL-PROTECTED BUILDING SUBJECTED TO SEVERE HEAT, MAIN EXCHANGE OF PACIFIC STATES TELEPHONE AND TELEGRAPH COMPANY, SAN FRANCISCO.

Rolling shutters, self-supporting brick walls, concrete floors, and concrete protection for columns and girders. Photograph by Richard L. Humphrey.

B. WARPING OF PLASTERED METAL-LATH COVERING BY FIRE, MURPHY BUILDING, SAN FRANCISCO.

Photograph by Richard L. Humphrey.

A. ROOF TRUSSES DAMAGED BY HEAT, THROUGH FAILURE OF TERRA-COTTA COVERING, MUTUAL LIFE BUILDING, SAN FRANCISCO.

Photograph by Richard L. Humphrey.

B. EFFECT OF SETTLING OF GROUND SUBJECTED TO EARTHQUAKE VIBRATIONS, STEEL-FRAME BUILDING UNDER CONSTRUCTION.

The concrete basement walls were not reenforced. Post-office in the background. Photograph by Richard L. Humphrey.

A

B

FAILURE OF HOLLOW TERRA-COTTA TILE FIREPROOFING.

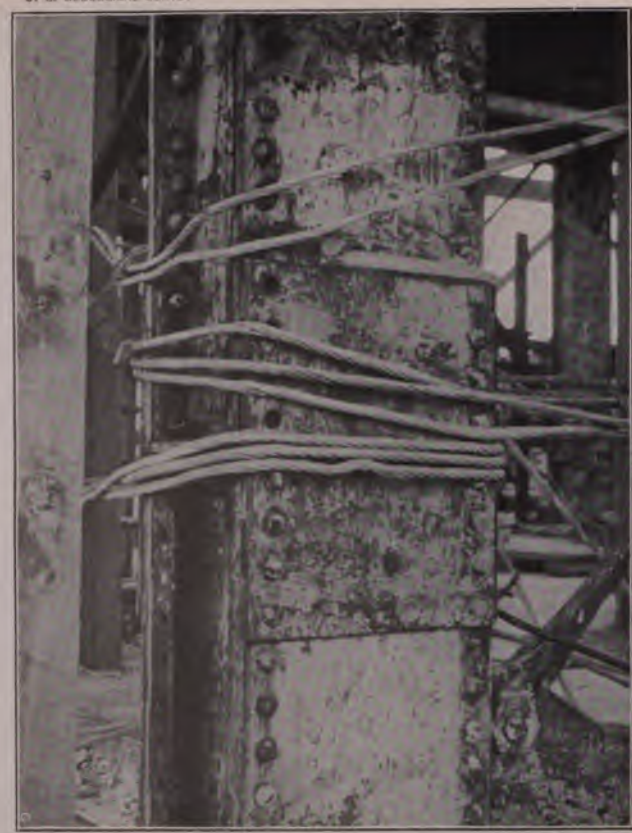
A, First story of Spring Valley Water Company's Building, San Francisco (photograph by John Stephen Sewall); *B*, Mills Building, San Francisco (photograph by Richard L. Humphrey). The lower webs of the floor tiles were spalled or taken entirely off by the fire.

A. BRICKWORK THROWN DOWN BY EARTHQUAKE VIBRATION, TOWER OF UNION FERRY BUILDING, SAN FRANCISCO.

Note bending of time-ball shaft. Photograph submitted by Richard L. Humphrey.

B. EFFECT OF SEVERE SHAKING ON WELL-BONDED BRICKWORK FILLED WITH GOOD MORTAR, TOWER OF UNION FERRY BUILDING.

Note sagged tie-rod, stretched by the racking of the structure. Photograph by John Stephen Sewell.



A

B

SHEARED RIVETS, TOWER OF UNION FERRY BUILDING, SAN FRANCISCO.

A, In column cover plate; *B*, In diagonal connection. Photographs by Richard L. Humphrey.

A. BUCKLING OF BASEMENT COLUMN DUE TO FAILURE OF PLASTERED METAL-LATH FIREPROOFING, RIALTO BUILDING, SAN FRANCISCO.

Photograph by Richard L. Humphrey.

B. DAMAGE SAID TO HAVE BEEN CAUSED BY DYNAMITE, RIALTO BUILDING.

Photograph by John Stephen Sewell.

A. FAILURE OF BASEMENT COLUMN DUE TO FIRE, SLOANE BUILDING, SAN FRANCISCO.

B. FAILURE OF TERRA-COTTA TILING AND METAL-FRAME WIRE-GLASS WINDOWS BY FIRE, LIGHT-WELL COLUMN, WELLS-FARGO BUILDING, SAN FRANCISCO.

A. COLLAPSE OF BUILDING DUE TO BUCKLING OF COLUMNS, SPRING VALLEY WATER COMPANY'S BUILDING, SAN FRANCISCO.

Photograph by Richard L. Humphrey.

B. FAILURE OF TERRA-COTTA TILE COVERING IN FIRE, UNION TRUST COMPANY'S BUILDING, SAN FRANCISCO.

Photograph by Richard L. Humphrey.

A. AN UNFINISHED STEEL SKELETON, WITH NONFIREPROOFED STEEL WORK.

B. UNPROTECTED STEEL FRAME AND GENERAL FLIMSY CONSTRUCTION, COWELL BUILDING.

EFFECTS OF HEAT ON STEEL WORK, SAN FRANCISCO.

Photographs by Richard L. Humphrey.

A. ENDURANCE OF BRICK VAULT.

This vault, which was in the original Wells-Fargo Building, San Francisco, passed the fire test satisfactorily, although the building was completely destroyed. Note the defective steel "fireproof" safes near by. Photograph by Richard L. Humphrey.

B. ABSOLUTE FAILURE OF SO-CALLED "FIREPROOF" SAFES.

In the rear are the Palace Hotel (at the left) and the Crocker Building (at the right). Photograph by Richard L. Humphrey.

A. EARTHQUAKE DAMAGE TO BRICK STACK OF STAR SECTION, VALENCIA STREET POWER STATION, SAN FRANCISCO.

Showing peculiar crack in reentrant angle. Photograph by Richard L. Humphrey.

B. GENERAL EARTHQUAKE EFFECT ON FRAME BUILDINGS SITUATED ON ALLUVIAL SOIL, HOWARD STREET, SAN FRANCISCO.

Photograph by A. C. Lawson

DESTRUCTION BY FIRE, SAN FRANCISCO.

View looking west from Telegraph Hill, showing unburned houses on summit of Russian Hill. St. Francis Roman Catholic Church, with its excellent brick walls, in the foreground. Photograph submitted by Frank Soulé.

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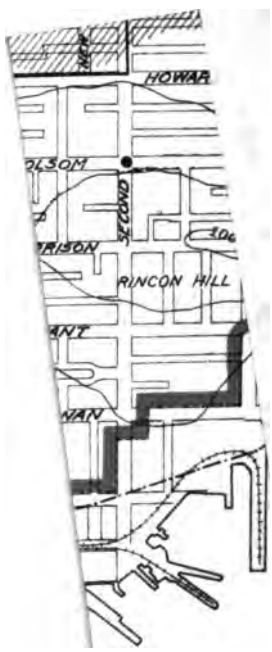
13. Dewey monur
14. Emporium.
15. James Flood
16. Powell street.



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DEPARTMENT OF THE INTERIOR

UNITED STATES GEOLOGICAL SURVEY

GEORGE OTIS SMITH, DIRECTOR

A STUDY OF

FOUR HUNDRED STEAMING TESTS

MADE AT THE FUEL-TESTING PLANT, ST. LOUIS, MO.
IN 1904, 1905, AND 1906.

BY

LESTER P. BRECKENRIDGE

WASHINGTON
GOVERNMENT PRINTING OFFICE
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PREFACE.

The fuel tests discussed in this paper were made under two Heine water-tube boilers by the boiler division of the United States Geological Survey fuel-testing plant at St. Louis, Mo. These tests began during the Louisiana Purchase Exposition, in 1903, and have been in progress since that time. The coals tested have been collected from all the prominent fields of the United States.

It has been the object to compare fuels by determining the evaporative performance of the boilers when using the various coals. Careful and complete observations have been made with each coal, so that it should be possible for engineers to determine from an examination of the records whether the conditions of the tests were favorable or unfavorable for the character of the coals tested.

The results of tests by the several divisions of the fuel-testing plant that have been published thus far appear in (*a*) Bulletins Nos. 261 and 290 of the United States Geological Survey, giving preliminary reports of the operations of the plant; (*b*) Professional Paper No. 48 of the Survey, giving complete and detailed information of the tests made during the Exposition.

The steaming tests were in charge of D. T. Randall during the Exposition period and of Walter T. Ray since that time. These men have been ably assisted by a corps of trained observers and computers, who have been alert, patient, and painstaking.

As soon as a considerable number of tests were available, it seemed desirable to begin a comparison of the various tests on the basis of such usual factors as over-all efficiency, rate of combustion, temperature of escaping gases, evaporation per square foot of heating surface, etc. It soon developed that many interesting and apparently valuable results were brought out by these comparisons, and hence they were extended. The discussions of facts led to a search for theories, and the men of the division sought out available literature bearing on the various subjects under discussion. Thus has accumulated the material here presented. It is not the work of any one, but of all.

To Messrs. Walter T. Ray, Henry Kreisinger, and Harry W. Weeks should be accorded especial credit for preparing the larger part of this material. Except for the cooperation and careful work of the chemical division, under the supervision of Dr. N. W. Lord, much of the work here reported would not have been possible.

Many of the relations submitted have been worked out at the suggestion of different engineers who were interested in particular phases of the work. Some repetition in the matter presented is perhaps unavoidable on account of the nature of the subject. Possibly much that is new has developed during the discussion, because never before have 400 boiler tests been made under two boilers (exactly alike) with coals and lignites from all sections of the United States and with all tests fired by the same expert fireman.

Acknowledgment is gratefully made to the many engineers of the country for helpful suggestions and kind criticisms that have come to me while endeavoring to direct the tests of this division so that they would prove of the greatest value to the industries of the nation, and to those engineers whose problem is still to furnish boilers of greater capacity and furnaces of higher economy. It must not be forgotten that all discussion is based on the results obtained in a single furnace with one type of boiler, but many of the results should have wide application in any furnace and under any type of boiler. Helpful suggestions or criticisms from manufacturers or engineers are again invited.

In submitting this paper I desire to thank Dr. Joseph A. Holmes, expert in charge of the fuel-testing plant, for his uniformly courteous consideration of the plans and needs of the boiler division and for the freedom which he has always allowed us in carrying on the work. We have appreciated his confidence and can only hope that it has been merited.

L. P. Breckenridge,
Engineer in Charge of the Boiler Division.

Urbana, Ill., *January 14, 1907.*

A STUDY OF FOUR HUNDRED STEAMING TESTS.

By Lester P. Breckenridge.

INTRODUCTION.

By Walter T. Ray.

Origin of the bulletin.—As the so-called "boiler tests," made by the fuel-testing plant at St. Louis, gradually accumulated, it became evident to the men making them that a great deal of incidental work was assuming the shape of a considerable compilation of plottings and calculations of various matters pertaining to the tests, and that certain details of the work were beginning to shed light on the inner reasons for the unreliability of tests of coals made under steam boilers. Much research work was being done in the boiler room simultaneously with the steaming tests proper, and of this work also certain details shed light on the same unreliabilities.

It was originally intended to insert these results in the regular bulletins of the fuel-testing plant, but the further the work went the less of a basis for general conclusions it seemed to be. For this reason publication was postponed until a large amount of matter was on hand. In order to avoid undue bulk, no account of most of the work itself is given. Many of the negative results obtained are presented, however, on the general principle that negative results are usually worth as much as positive results.

Scope of the work.—An especially striking instance of the value of negative results was noted in an attempt to check up the readings of an optical pyrometer used on the combustion chamber by calculating the initial temperatures of the gases entering the boiler in each test, so as to find whether the pyrometer read too high or too low when sighted on flame. The basis used for the calculation was the efficiency noted as "72*, efficiency of boiler, per cent" in the code of the American Society of Mechanical Engineers. The calculated temperatures of combustion were ridiculous, and were very puzzling for some weeks. Meanwhile a study was made of some chapters in John Perry's book, "The Steam Engine and Gas and Oil Engines," relating to the manner in which fluids give up heat and momentum, and

making application of these principles to steam boilers. A development of these ideas and their application to the apparatus used in these tests constitutes what is believed to be the most valuable part of this bulletin. It is thought that a fairly trustworthy separation has been effected for most tests of the true boiler efficiency and the percentage of completeness of combustion. Apparently the former is constant, as the theory indicates, and the "practical" boiler efficiency differs from it by only a very few per cent, the main cause of the difference apparently being that as a rule all of the fuel is not burned.

All of this work has been done with the hope of discovering new guiding principles for use in forecasting the results of burning any given fuel more accurately than can now be done from chemical analyses and observation of physical characteristics. It is true that at present the choice of coals in any market for any given use can be narrowed down to perhaps 20 per cent of the coals considered by a consideration of market price, freight charges, chemical analysis, heating value, and physical characteristics; but the ambition of the boiler division is to work toward that completeness of knowledege whereby about three-fourths of the 20 per cent can also be discarded after laboratory investigations.

It is also the intention of the boiler division to study the principles of fuel combustion to such advantage that much coal can be saved, and that cheap fuels can be used in certain operations where higher-priced ones are now considered necessary. Such savings will really redound to the benefit of producers of the best fuels of all grades quite as much as to the benefit of consumers. A number of new lines of work are suggested in the text; several of these it is planned to take up soon, and some of them may give data for determining the burning qualities of fuels independently of the apparatus in which the process takes place.

Perhaps the most important reason for doing the research work, and for making so many comparisons of the data obtained from all tests, was the feeling that the testing of fuels under boilers is at best only approximately comparative. In short, it was the feeling that we were on the wrong track, without knowing of a better one, which led us to do the research work.

This work was performed and the results were prepared for publication under the direction of Prof. L. P. Breckenridge, engineer in charge of the boiler division, by the following men located at St. Louis: Walter T. Ray, Henry Kreisinger, Harry W. Weeks, Charles H. Green, Robert H. Kuss, Loyd R. Stowe, William M. Park, Ralph Galt, Fred O. Pahmeyer, Raeburn H. Post, George S. Pope, Gilbert E. Ryder, Fred J. Bird, Carl J. Fletcher, and Perry Barker.

Many of the opinions given in this volume are not shared by all the authors; some of them represent a compromise. The responsibility of selecting materials and deciding what views should be taken on *many points* naturally fell on Mr. Ray, who was the engineer locally

in charge of steaming tests at St. Louis, and to him is to be charged the fault of any unjustified expressions of opinion or mistakes in text or figures.

It is realized that future work may show that some of the opinions advanced herein are faulty, and consequently the right is reserved to change them. Nevertheless, this work as a whole expresses the best present knowledge of the boiler division, and is given out for others to think about. It should be distinctly stated that the chemical division of this plant is in no way responsible for anything herein, although its members have been consulted on some points and have very kindly made many suggestions.

Special attention is called to the "General conclusions," page 174, and to the paragraphs entitled "Commercial considerations," page 177.

RELATIONS OF TEST DATA.

RATE OF COMBUSTION.

Fig. 1 should be considered in connection with fig. 2, the same tests being classified in both charts according to the pounds of dry coal burned per square foot of grate per hour. The figures in the small circles indicate the number of tests considered in determining the position of the points near which they are placed. In fig. 1 curve No. 1 is high for low rates of coal consumption, because it is hard to keep down the air supply. Curve No. 2 shows the per cent of stack loss. It drops at first because the air supply increases. (See curve No. 1.) It rises on the right because the gases leave the boiler at higher temperature, as shown by curve No. 3. The coals of the tests averaged on the left of the chart are in general of good quality and slower burning than those in the center; those on the right are somewhat lignitic in character. This perhaps explains why curve No. 3 is low in the center; the combustion-chamber temperatures were lower there, hence the flue temperatures were also lower. But, after all is said, the reason is in doubt, because the maximum flue-temperature range is only 50° F.

On comparing the flue-temperature curves of figs. 1 and 3 a difference will be seen in the left-hand ends. With reference to this curve in fig. 1, the coals toward the left end become better in quality and higher in "fixed carbon," so that although they burned slowly the combustion-chamber temperatures were fairly high, and consequently the stack temperatures were higher than in the center of the curve. With reference to the analogous curve of fig. 3, the coals to the left are both poorer and slower burning, and a larger air excess was used, relatively, which made the combustion-chamber temperature lower; consequently the flue temperature was lower. Further, the lower curve of fig. 1 is perhaps drawn a little too high at the left end, and that of fig. 3 a little too low.

Fig. 2 should be considered in connection with fig. 1. Little can be said of curve No. 1 (fig. 2), except that it rises slightly with increasing rates of combustion—about three to five times as much

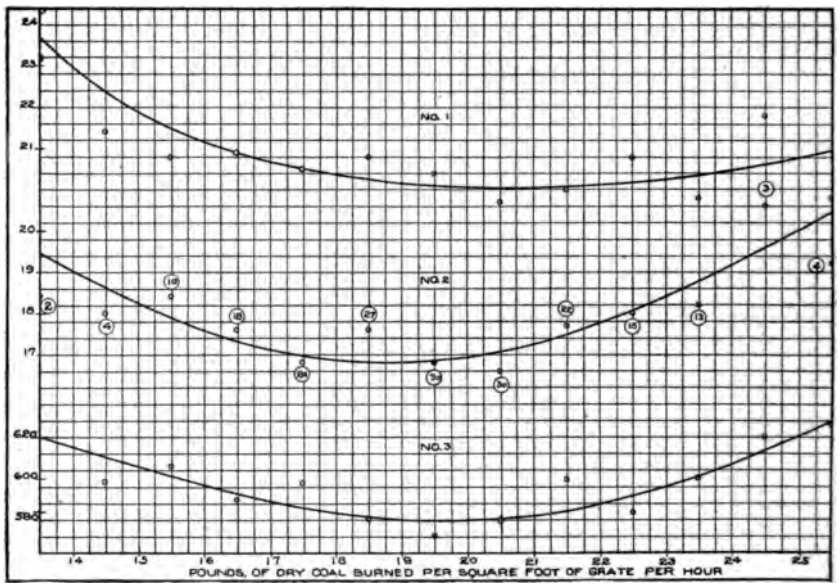

FIG. 1.—Relations of rate of combustion to pounds of dry chimney gases per pound of "combustible" (curve No. 1); per cent of loss up the stack, from heat balance (curve No. 2); and flue-gas temperature (°F.) taken under stack damper (curve No. 3). Classified on rate of combustion as basis; tests 126–355.

as the broken line just below, connecting the CO averages. The rising of both is perhaps a consequence of decreasing air supply per

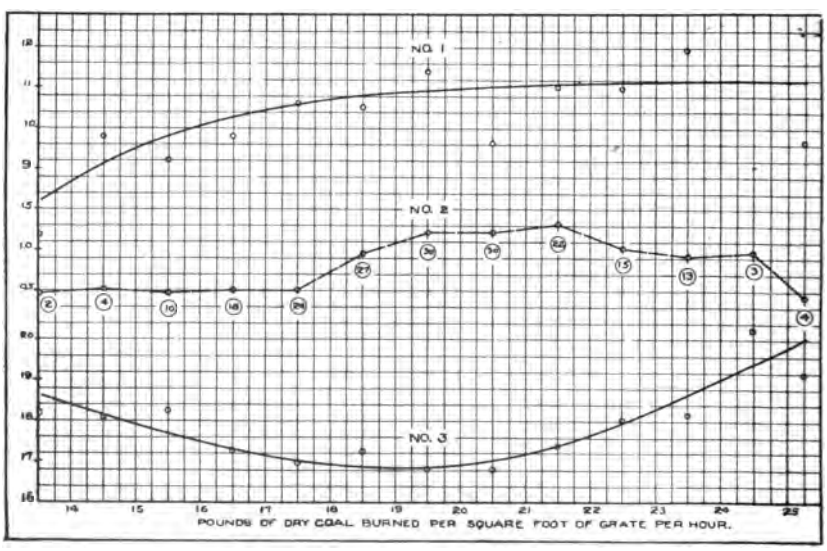

FIG. 2.—Relations of rate of combustion to per cent unaccounted-for loss (curve No. 1); per cent of CO loss (curve No. 2); and per cent of loss up the stack (curve No. 3). Classified on rate of combustion as basis; tests 126–355.

pound of "combustible," as indicated by curve No. 1 of fig. 1. Curve No. 3 of fig. 2 is a reproduction of curve No. 2 of fig. 1.

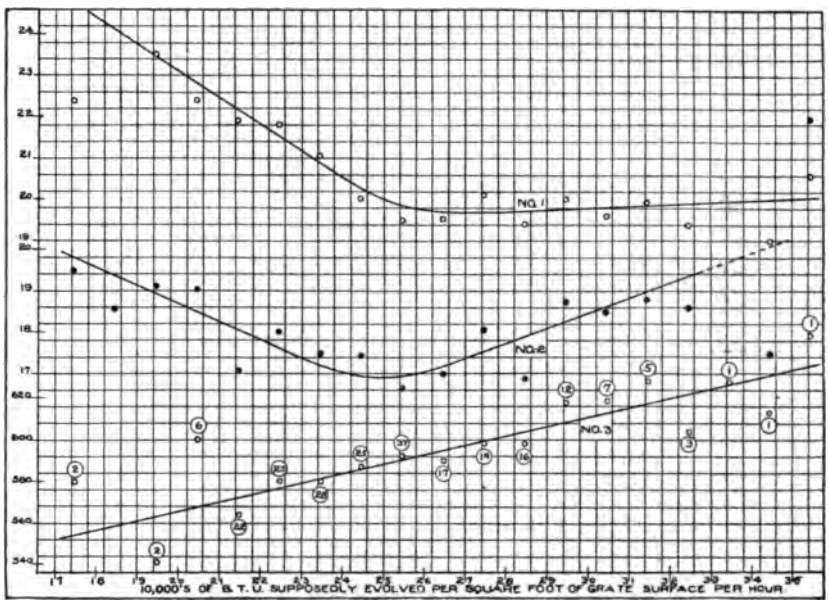

FIG. 3.—Relations of rate of heat evolution to pounds of dry chimney gases per pound of "combustible" (curve No. 1); per cent of loss up the stack (curve No. 2); and flue-gas temperature (°F.) (curve No. 3). Classified on rate of heat evolution as basis; tests 126–358.

SUPPOSED RATE OF HEAT EVOLUTION.

Fig. 3 should be considered in connection with fig. 4. In both charts the same tests are grouped according to the number of B. t. u.

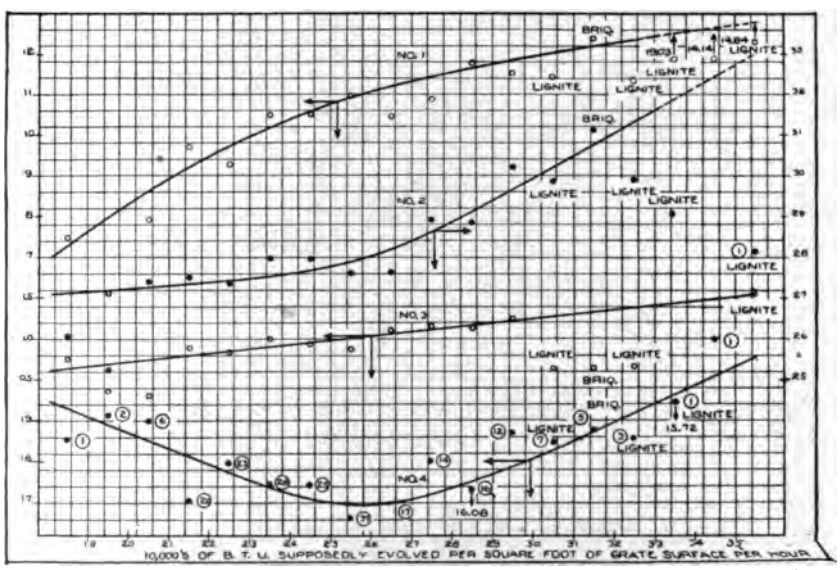

FIG. 4.—Relations of rate of heat evolution to per cent unaccounted for (curve No. 1); per cent unaccounted for *plus per cent of loss* up the stack (curve No. 2); per cent of CO loss (curve No. 3); and per *cent of loss up the stack* (curve No. 4). Classified on rate of heat evolution as basis; tests 126–358.

supposedly liberated per square foot of grate surface per hour. Had it been practicable, the six curves concerned would have been plotted on one chart. According to curve No. 1 the pounds of dry chimney gases per pound of "combustible" decrease rapidly at first, but for the right-hand half of the chart they remain constant. The left half of curve No. 2 shows a rapidly decreasing stack loss, which might be expected to remain about constant on the right, inasmuch as the pounds of dry chimney gases per pound of "combustible" remain constant. One explanation of its rising is that the circulation of water in the boiler fails to increase at as rapid a rate as the demands on it, in consequence of which the boiler is increasingly less efficient as a heat absorber, wherefore the gases escape at a higher

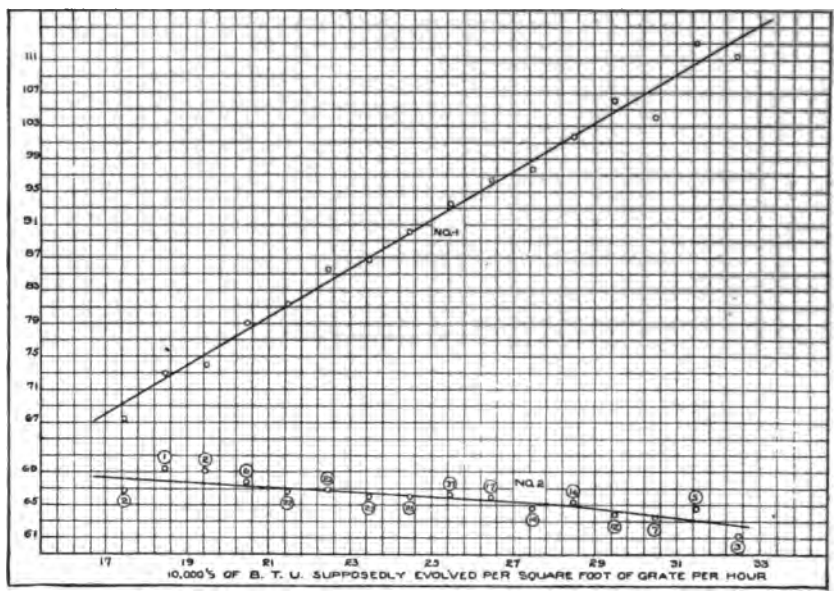

FIG. 5.—Relations of rate of heat evolution to per cent of rated capacity developed (curve No. 1) and efficiency 72* (curve No. 2), classified on rate of heat evolution as basis; tests 126–358.

temperature. This explanation would make curve No. 3 consist of two portions, the upward slope of the left half, which is due to rise of furnace temperature, being continued for the right half by the decreasing efficiency of the boiler.

For a comparison of the shapes of the flue-temperature curves of this chart and of fig. 1, see the text on the latter (p. 11).

Fig. 4 should be considered in connection with fig. 3. In both of these charts, as already stated, the same tests are classified on the basis of heat supposedly evolved; and here the emphasis is on the word "supposedly," for fig. 4 implies by circumstantial evidence that some of the fuel never burned. Curve No. 1, the per cent "unaccounted for," rises about 5 per cent, and curve No. 3, the per cent

of CO loss, rises nearly 0.5 per cent along the same range of heat supposedly evolved. The implication is that the rise of CO loss is merely an indication of greater losses not ascertained, due probably to incomplete combustion.

Curve No. 4 in this figure is the same as curve No. 2 of fig. 3, a tentative explanation of which is given in the text relating to that figure (p. 13). The arrows on the curves indicate which coordinate scales are to be used with each curve.

Fig. 5 is based on about two hundred tests of coals from all parts of the country. It is not true to any great extent that the better coals are represented more in some parts of the curves than in others; therefore the following deductions are fairly reliable. The 10,000's

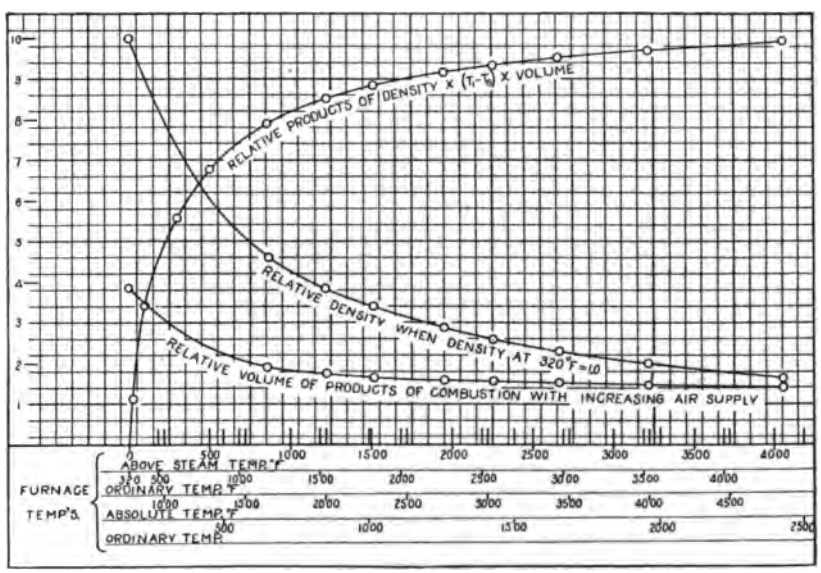

FIG. 6.—Theoretical curves of factors affecting heat absorption, based on furnace temperature.

of B. t. u. supposedly evolved per square foot of grate surface per hour was calculated by deducting the heat loss in CO and in combustible dropping through the grate from the heat value of the coal fired. Curve No. 1 shows that within the usual working range the capacity is very nearly a straight-line function of the heat supposedly evolved in the furnace. Curve No. 2 is especially significant, showing a decided falling off in efficiency 72*,[a] as the amount of heat supposedly evolved increases. By reference to the lower curve of fig. 6 it will be seen that the volume of the gases of combustion from 1 pound of carbon is nearly constant whatever the air excess used, providing this excess is within reasonable limits of operation. Therefore the volume of gases passing through the combustion chamber per

[a] For definition of efficiency 72* see "Efficiencies" in the glossary (p. 181).

second is almost entirely a function of the coal burned, or, as given here, of the number of B. t. u. supposedly evolved per hour; whence the velocity of the gases as they pass from the fuel bed to the boiler entrance is proportional to the number of B. t. u. supposedly evolved. The emphasis is on the word "supposedly," for it is likely that the incompleteness of combustion increases as the time occupied by the gases in traveling from fuel bed to boiler decreases. This reduction of time for combustion is perhaps the reason for the common remark that when a combustion chamber is "worked too hard" its efficiency decreases; it may mix a large volume of gases as thoroughly as it does a fraction of the volume, but the time available for combustion is less.

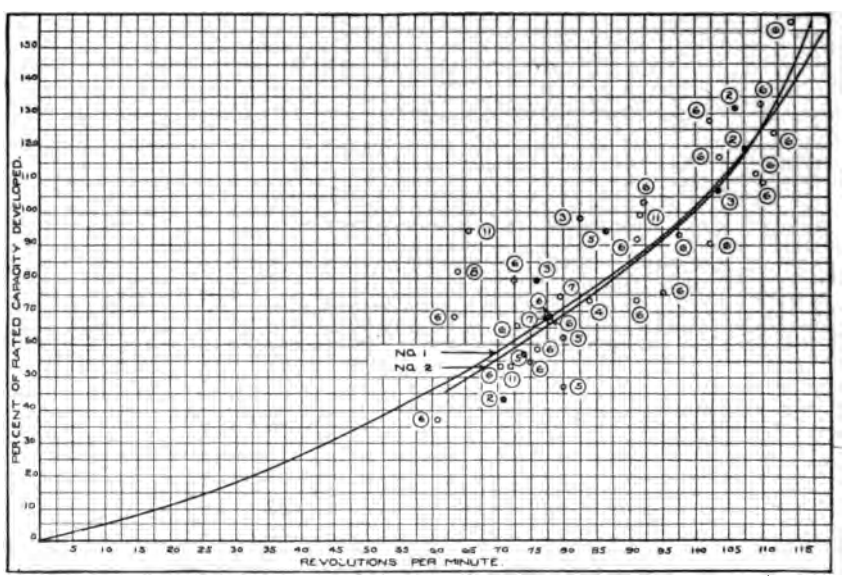

FIG. 7.—Velocity of water circulation in boiler as affected by rate of steaming: Curve No. 1, determined by classifying on revolutions per minute; curve No. 2, determined by classifying on per cent of rated capacity developed. Instrument for measuring circulation placed in first tube left of center in second row from bottom at rear of boiler.

Another probable cause of the drop of over-all efficiency (efficiency of furnace and boiler) is the fact that the circulation of the water inside of the boiler does not keep up with the capacity. Fig. 7 shows that the circulation of water does not increase in proportion to the capacity as it should. The consequence is that the water does not take the heat fast enough from the metal of the boiler, which therefore remains hotter at the higher capacities. When the heat-absorbing surface is at higher temperature less heat is available for the boiler, and hence the over-all efficiency drops. (See p. 137.)

On comparing the curves of capacity rise of figs. 5 and 8 it will be noticed that a given percentage change in B. t. u. supposedly evolved is accompanied by a much greater change in capacity than is the same percentage change in pounds of dry coal burned. The explanation is that as the pounds of dry coal burned per square foot of grate become less, the B. t. u. evolved do not on the average become much less, because some high-grade coals burn slowly; vice versa, some coals low in heating value burn rapidly. The capacity curve of fig. 8 may well have less slope than that of fig. 5. In studying the curves of fig. 8 it will also be noticed that when the pounds of dry coal burned per hour are doubled, efficiency 72* falls 5 per cent;

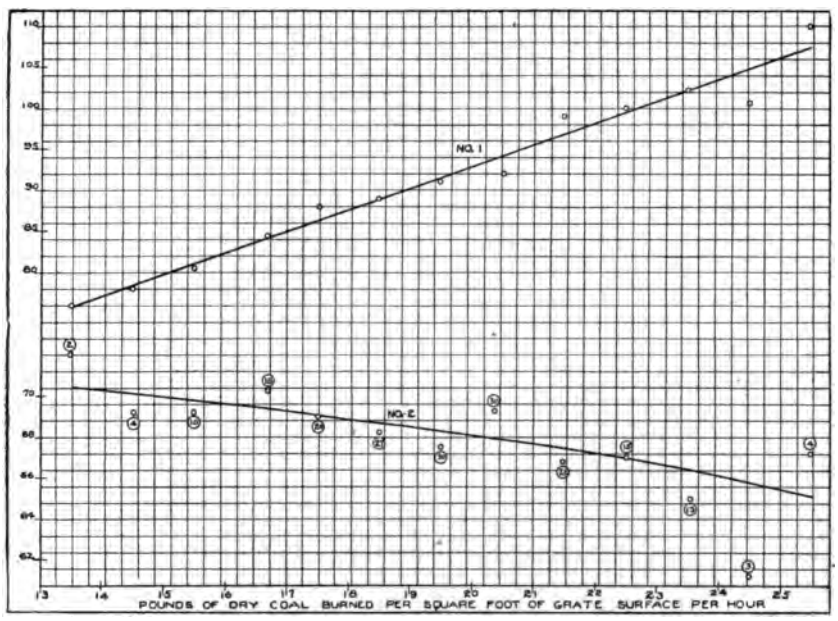

FIG. 8.—Relation of pounds of dry coal burned per square foot of grate to per cent of rated capacity developed (curve No. 1) and efficiency 72* (curve No. 2). Tests 126-355.

whereas, referring to fig. 5, when the number of B. t. u. supposedly evolved is doubled, efficiency 72* falls 7 per cent, indicating both more incompleteness of combustion and poorer heat absorption.

Curves determined by classification of various coals on the basis of pounds of dry coal burned per square foot of grate per hour are only approximate; those based on the heat supposedly (or ostensibly) evolved are of more value. The only correct classification would be on heat actually evolved as a basis. However, this involves the determination of the losses due to incomplete combustion of hydrocarbons and of solid particles of carbon escaping in smoke, and such determinations are very difficult to make, perhaps impossible.

COMBUSTION-CHAMBER TEMPERATURE.

Fig. 9 shows variation of temperature with firing in the Heine furnace. Variations of the temperatures in the fuel bed, over the fire, and in the combustion chamber are given with two very different coals. These temperatures were taken with the Wanner optical pyrometer (fig. 10), which was standardized before and after each series of observations. Every series of readings was taken without

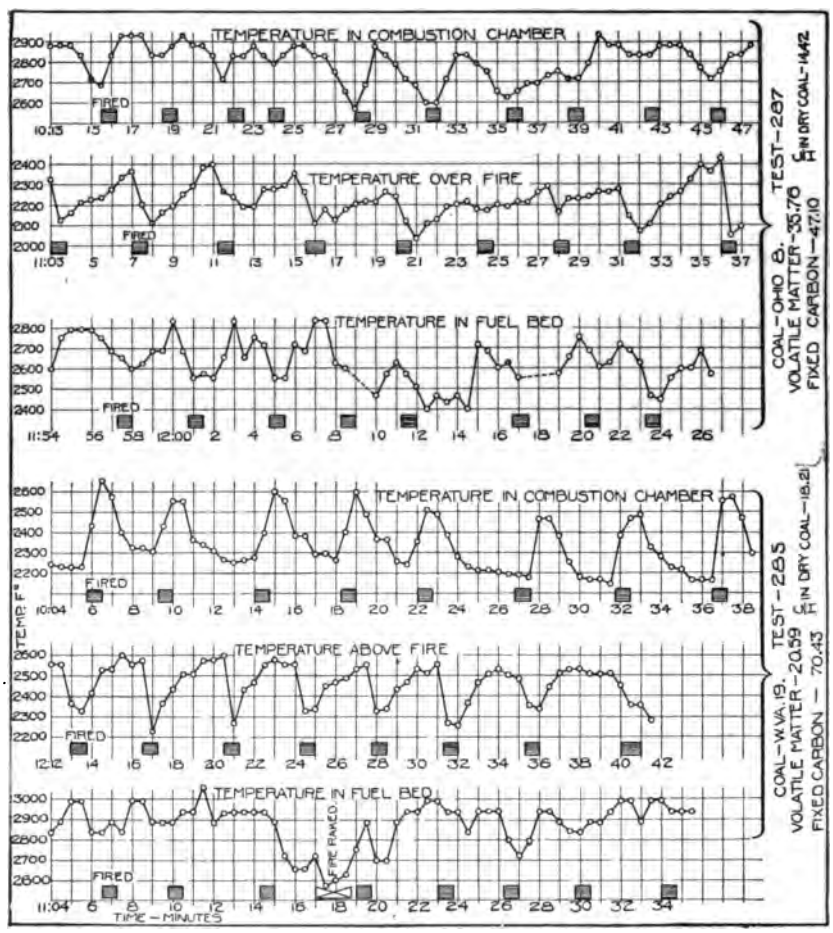

FIG. 9.—Variation of temperature with firing in Heine furnace.

disconnecting the pyrometer from the battery after the standardization. Owing to the fact that only one pyrometer was available the temperatures were not taken simultaneously. The chart (fig. 9) shows clearly the three things following:

1. During and shortly after each firing the temperature over the fire and to some extent the temperature in the fuel bed drops, and *the temperature* in the combustion chamber rises. The explana-

tion of this variation is that the distillation of "volatile matter" is a cooling process and is undoubtedly a partial cause of the drop of temperature in the fuel bed and over the fire, but the volatile matter distilled is carried into the combustion chamber, where it burns, causing a rise of temperature there.

2. The peaks in the curve for combustion-chamber temperature and the depressions in the curve for over-fire temperature are wider for Ohio No. 8, a coal high in volatile matter, than for West Virginia No. 19, a coal low in volatile matter, indicating that the volatile matter is distilled off and burned in shorter time in the West Virginia coal than in the Ohio coal.

3. Combustion-chamber temperature is much higher with Ohio No. 8 than with West Virginia No. 19, while fuel-bed and over-fire temperatures are higher with West Virginia No. 19 than with Ohio

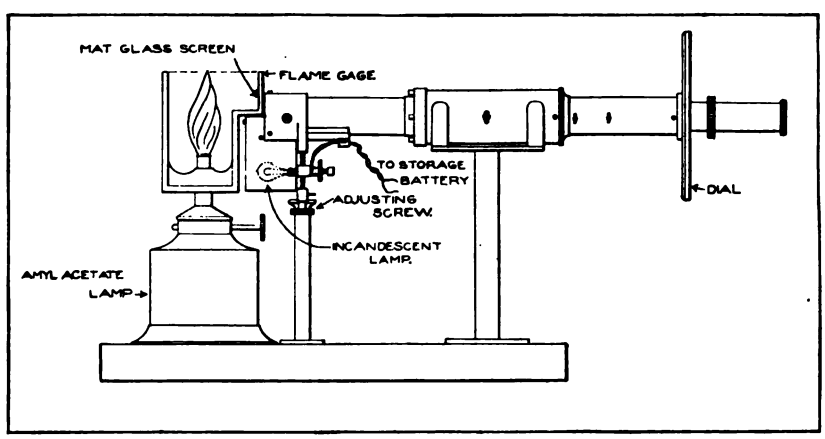

FIG. 10.—Wanner optical pyrometer in position for standardizing.

No. 8. This contrast indicates that most of the West Virginia No. 19 coal burns on the grate and only a little in the combustion chamber, while the opposite is true of Ohio No. 8.

The two similar curves of fig. 11 are based on all tests (126–355) having combustion-chamber temperatures as read by the Wanner optical pyrometers. Coals from all parts of the country are included. To obtain the upper curve the tests were grouped according to pounds of dry coal burned per square foot of grate per hour; to obtain the lower curve they were grouped on 10,000's of B. t. u. supposedly evolved per square foot of grate per hour, the supposition being that all of the potential heat is liberated, after deducting for the loss of combustible in ash and for CO loss.

The rise in temperature throughout the whole range, for a doubling of the base values, is very nearly the same in the two curves. A significant feature of both curves is that the combustion-chamber

temperature rises with the amount of heat liberated in the furnace; perhaps because conditions of combustion grow better at first, on advancing from poor coals at the left to the better ones in the center.

Curves No. 1 in fig. 1 and No. 1 in fig. 3 show the direct cause of the decreasing rise in combustion-chamber temperature.

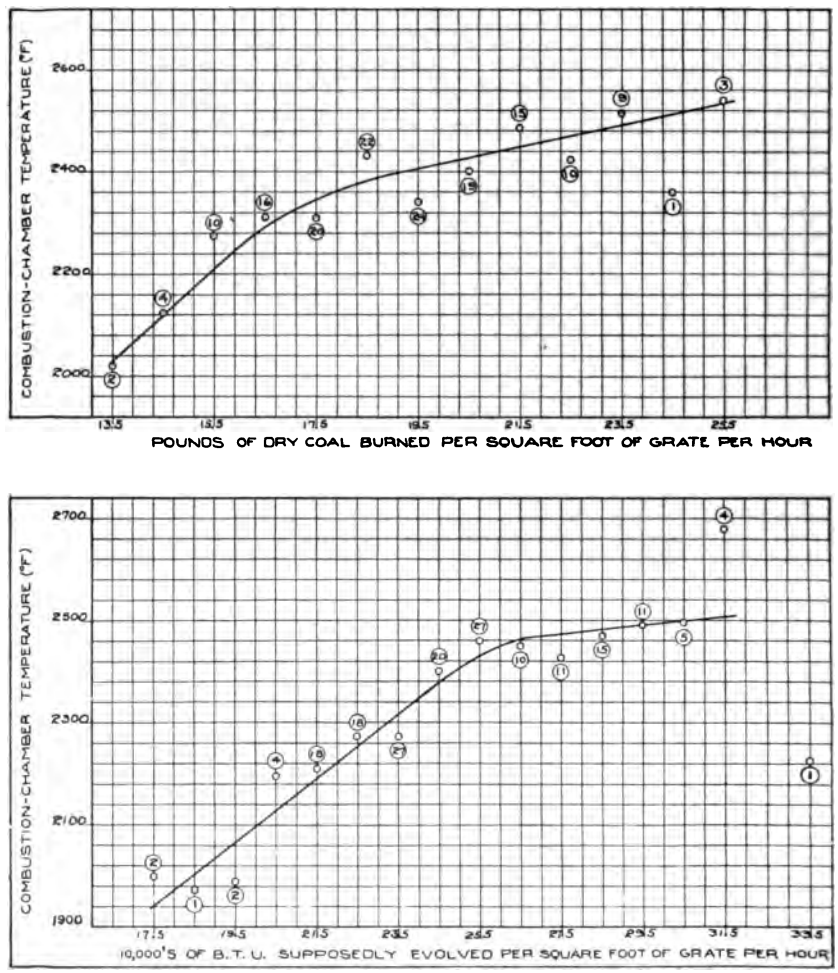

FIG. 11.—Combustion-chamber temperature as a function of pounds of dry coal burned per square foot of grate per hour, classified on basis of pounds of dry coal burned (upper curve); and 10,000's of B. t. u. supposedly evolved per square foot of grate per hour, classified on basis of 10,000's of B. t. u. supposedly evolved (lower curve). Tests 126-355.

The curves of fig. 12 are based on one class of coals—those from Illinois and Indiana. The only striking showing is that the code "boiler efficiency" (72*) is practically constant throughout the whole range of furnace temperature. All these coals are apt to *evolve* compounds difficult to burn, and thus it is that the lower the

percentage of oxygen present the less complete the combustion, notwithstanding the higher temperature resulting. With these coals, therefore, the decreasing completeness of combustion in our apparatus with rise of temperature seems to offset the increasing efficiency of the boiler as a heat absorber, which is only about 10 or 12 per cent within the range 1,850° to 2,850° F., according to the chart on page 141.

In this chart, as in all others, where capacity is shown as a function of furnace temperature, the two rise together. This relation will be clear on remembering that much heat is absorbed through the tile roof of the furnace; and the greater the amount of coal burned the less in percentage will this absorption amount to, so that the temperature at the last point of combustion is higher.

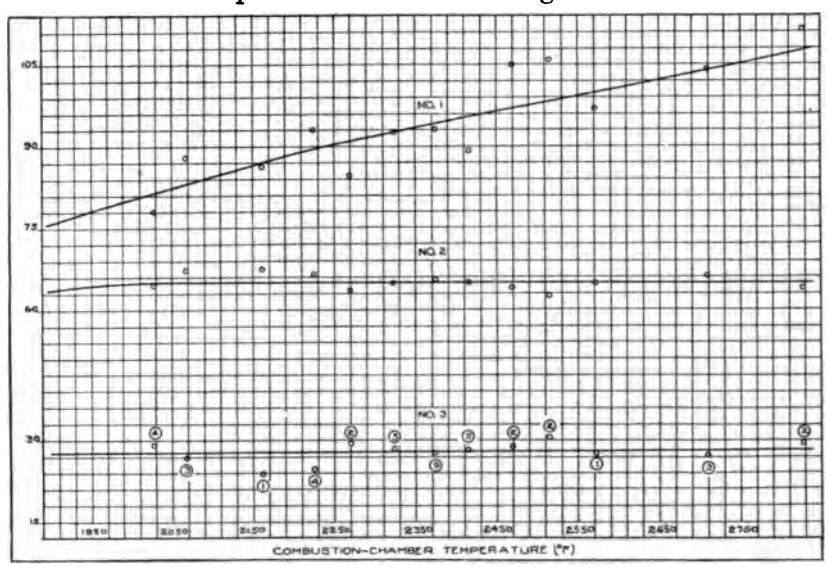

FIG. 12.—Relations of combustion-chamber temperature to per cent of rated capacity developed (curve No. 1); efficiency 72* (curve No. 2); and per cent unaccounted for plus per cent of loss up the stack (curve No. 3). Classified on basis of combustion-chamber temperature (°F.), Illinois and Indiana coals being used.

Fig. 13 is a companion to fig. 14, both charts being based on combustion-chamber temperature.

The arrows on the curves of fig. 13 indicate which coordinate scales are to be used with each. These thirty analyses were made at intervals of twenty minutes, on flue gases from the base of the stack, the combustion-chamber gases having been diluted with air by infiltration after entering the boiler. The curves of fig. 14 were computed on analyses of samples (taken half-hourly during about sixty tests) from the rear of the combustion chamber, through the water-jacketed gas sampler (fig. 15) described on page 154, so that these samples were probably undiluted.

As the temperature of combustion rises the oxygen percentage drops in a straight-line ratio and the CO_2 curve rises in nearly the same way; but the CO curve rises sharply after about 2,500° F. (1,370° C., the temperature indicated by curve No. 4 of fig. 14) has been reached. Of course the composition of the gases as affected by temperature probably varies from coal to coal. It should be remembered that on the whole the optical pyrometer probably indicated considerably lower temperatures than actually existed, because when burning short-flaming coals, or when running at the lower capacities, little flame was visible, and the instrument was pointed at a side wall visibly cooler than even the clay-tube tiles forming the furnace roof.

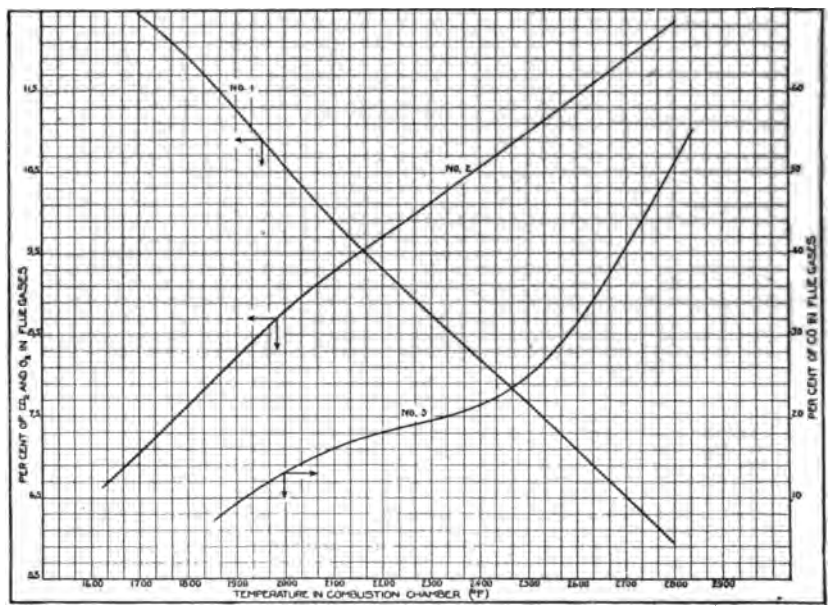

FIG. 13.—Relation of flue-gas composition to combustion-chamber temperature: Curve No. 1, O_2; No. 2, CO_2; No. 3, CO. Determined by averaging individual readings; tests 151-181.

Curve No. 1 of fig. 14 shows a gradual decrease in the Orsat totals as the temperature is raised, accompanied by reduced air supply. As the temperature rises the volume of hydrocarbons might be expected to increase, but their proportional volume would be so small that they would not affect this curve.

Fig. 16 is a graphic representation of the relation, in our apparatus, of combustion-chamber temperature to flue temperature for 212 tests, certain tests having doubtful readings being omitted. Both temperatures rise together. It is noticeable that the curve is less steep in the upper portion, which may be accidental, but indicates that at higher furnace temperatures the boiler absorbs a slightly

greater percentage of the heat available to it above steam temperature than at the lower furnace temperatures; that is, the true boiler efficiencies are not always the same. But no reliable conclusion can be drawn. The significance of the curve is general only.

Fig. 17 shows a classification of 217 tests on many coals from all parts of the United States based on temperature in the rear of the combustion chamber. In general the poorer coals fall at the left of

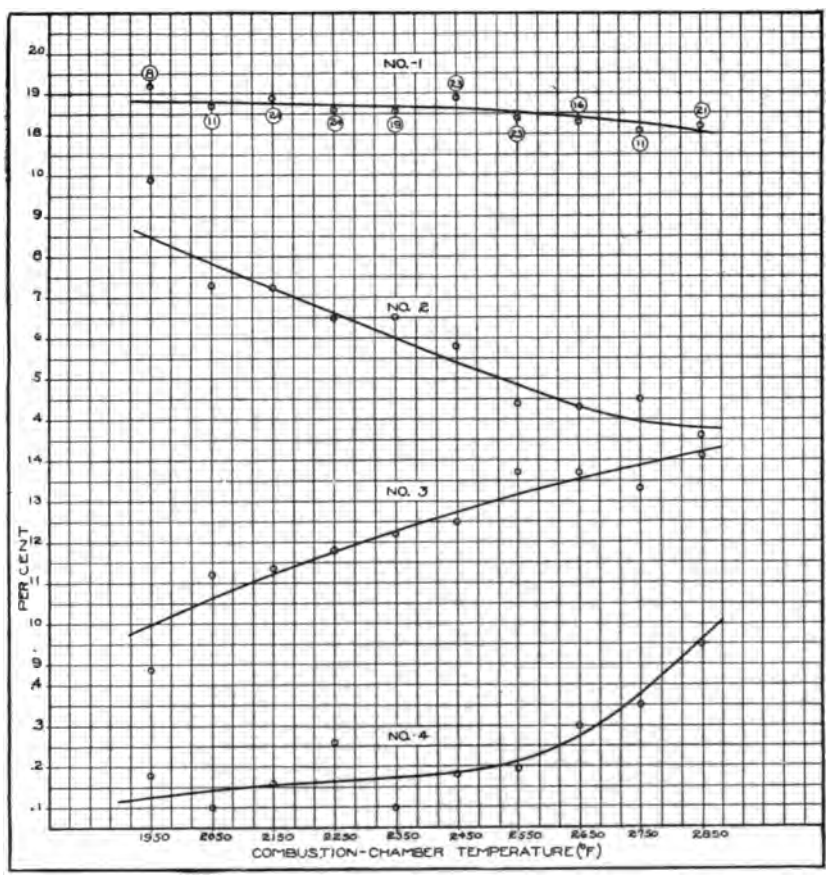

FIG. 14. Relation of gas composition to temperature, both in rear of combustion chamber: Curve No. 1, CO_2+O_2+CO; No. 2, O_2; No. 3, CO_2; No. 4, CO. Samples of gas taken through water-jacketed iron pipe; tests 318-382.

the chart. The most interesting showing (curve No. 1) is that the code "boiler efficiency" (72*) rises only 2 per cent as the combustion-chamber temperature rises from 1,800° to 2,700° F. This showing is in accordance with other charts and with the theory of boilers deduced on page 114, all being to the effect that a rise of about 1,000° F. in furnace temperature improves the efficiency of the boiler as a heat absorber only about 10 per cent. Most of this gain, however, is

offset by incompleteness of combustion chargeable to the restricted oxygen supply required to get the high temperatures.

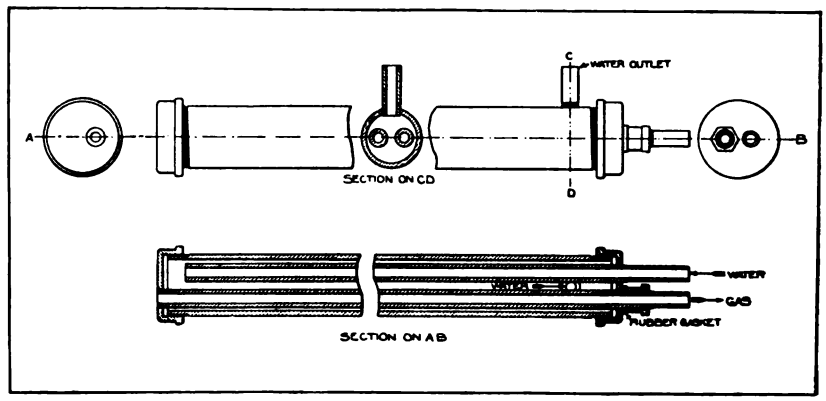

FIG 15.—Water-jacketed gas sampler.

Curve No. 2 shows a slight but persistent rise of CO_2 content in flue gases with increasing furnace temperatures, as is reasonable; it

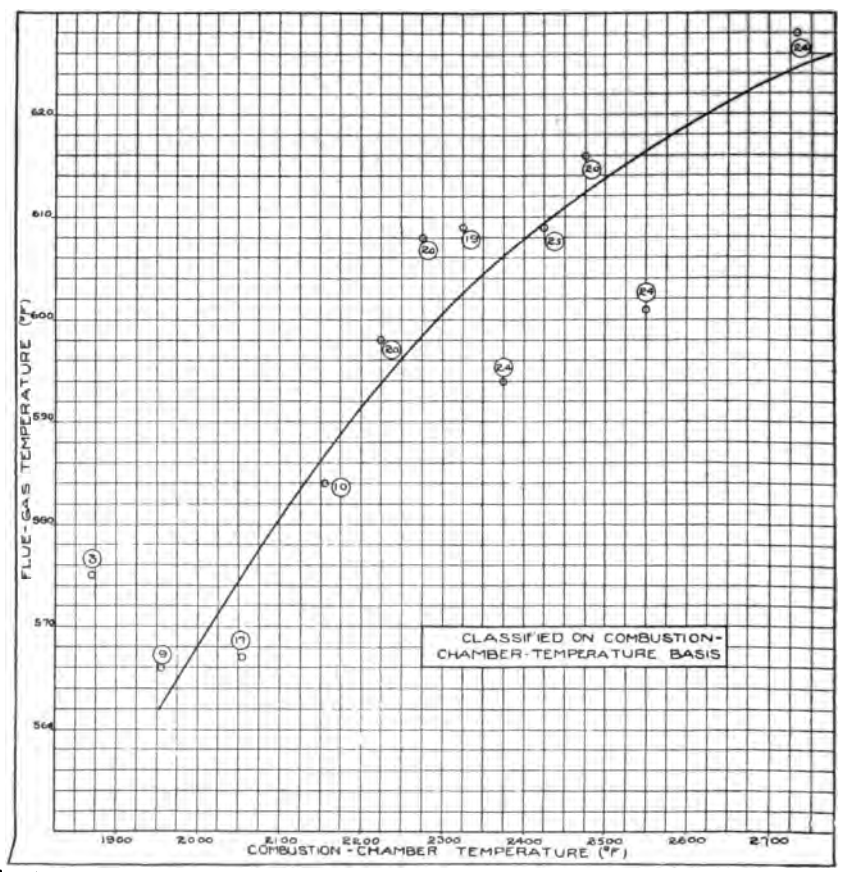

FIG. 16.—Relation of temperature in rear of combustion chamber to flue-gas temperature taken under stack damper; tests 150–400.

ought to be more marked. Air infiltration through the settings reduced the CO_2 percentage by 10 to 35 per cent in extreme cases.

Curve No. 3 shows a decided increase in the amount of steam made as the temperature rises. Since capacity is the comparative rate of absorption of heat by the boiler, it must necessarily increase with the rise of combustion-chamber temperature, if the equation

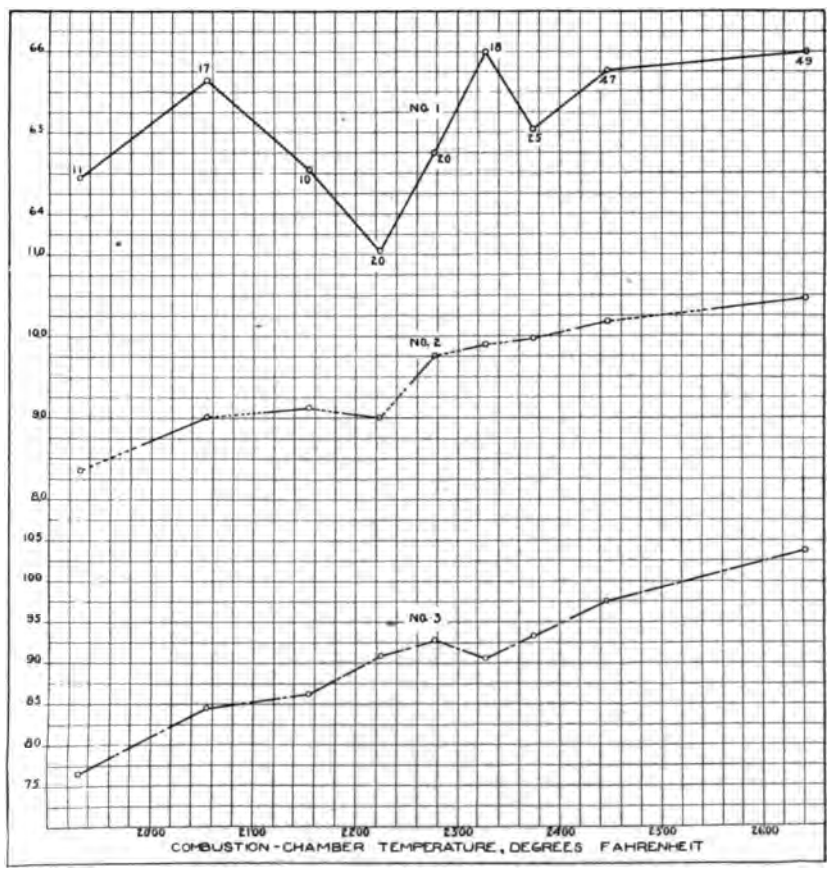

FIG. 17. Relations of combustion-chamber temperature to efficiency 72* (curve No. 1); CO_2 in flue gases, samples taken in hood (curve No. 2); and per cent of rated capacity of boiler developed (curve No. 3). Classified on combustion-chamber temperature as basis; tests 150–400.

used in the derivation of Perry's equation for true boiler efficiency, given on page 110, is true. The heat absorbed per second per unit of heating surface is

$$H = Cpv \ (T_1 - T_s).$$

Expressing the values of p and v in terms of T_1, we have

$$H = \frac{c}{T_1}.CT_1.C(T_1 - T_s) = K(T_1 - T_s).$$

The latter equation states that the capacity varies directly as the difference of the temperature of the furnace gases and the temperature of the steam.

As stated in the description of the baffle wall (p. 62), the construction and location were so chosen as to have the stream of gases leaving the furnace impinge against a solid part of the wall and break into many smaller streams, thus effecting mixing. It was intended to obtain a splashing effect similar to that seen when a stream of water is directed against a solid wall. That some such effect was attained was indicated by the high temperature taken through the opening just at the base of the bridge wall. This was invariably the highest temperature in the whole combustion space. Each of the temperatures given in the second column of the following table is the average of ten readings taken with the Wanner pyrometer at five different places in the furnace. These readings were taken successively through the side-wall openings from front to rear, so that the averages may be considered to represent simultaneous temperatures at all five places. Twenty-four readings were also taken in the same way by an exposed platinum and platinum-rhodium couple, connected to a galvanometer reading in degrees centigrade, giving the average temperatures at four places, as shown in the third column of the table.

Furnace temperature readings (test 359).

Place.	Wanner pyrometer.	Galvanometer.
	°F.	°C.
Fuel bed	2,470	913
Over fire	2,586	.....
Over bridge wall	2,826	1,075
Base of bridge wall	2,989	1,280
Rear of combustion chamber	2,447	1,035

The temperatures taken with the thermoelectric couple have only relative value, and are in fact much too low, the galvanometer having been recently repaired so that the divisions on the scale were not true degrees centigrade. The couple used had an exposed junction projecting from the end of a ⅜-inch iron pipe.

A. S. M. E. CODE BOILER EFFICIENCY (72*).

Fig. 18 consists of two charts. In the upper chart 293 tests are grouped according to efficiency 72*, the averages being plotted for each group of the percentages of CO and CO_2. All the higher efficiencies have low CO values and the lower efficiencies high CO values. The higher efficiencies have higher CO_2 values than the lower efficiencies, of course, though not much higher. The CO curve (No. 1) should be compared with curve No. 3 of fig. 19, which

is based on the same tests. The implication is the same—that high CO is a danger signal.

In the lower chart the same 293 tests are classified according to the percentage of CO_2 in the flue-gas analyses. The points plotted are the averages of the code "boiler efficiencies" (72*). It is evident that when once the CO_2 content gets beyond 9 per cent at the rear of the combustion chamber only about 1 per cent more—at most only 2 per cent—is to be gained by raising it higher. The per-

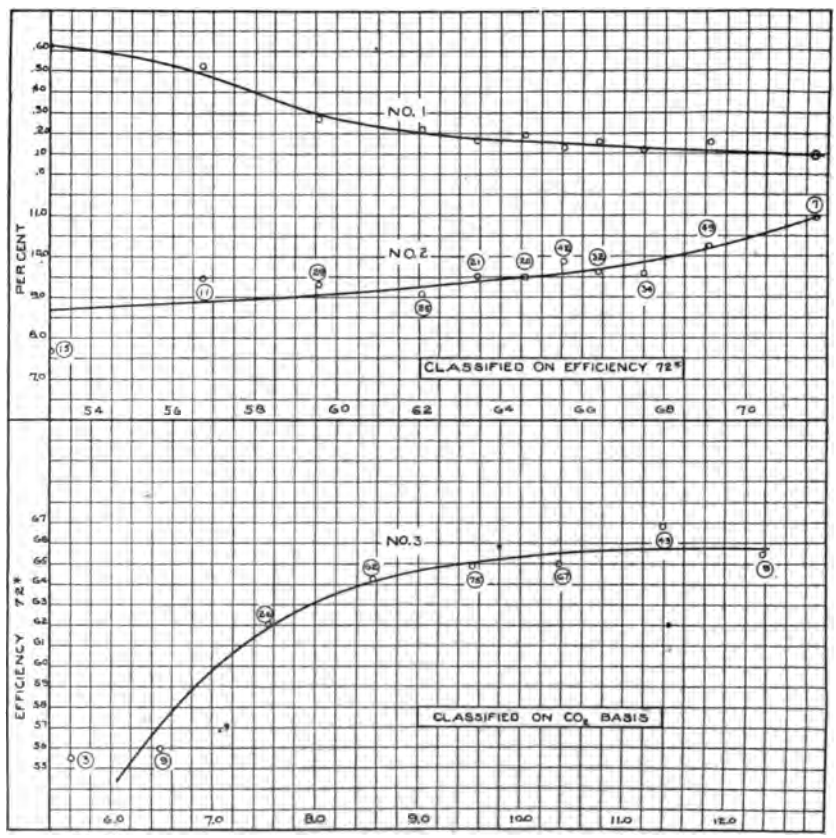

FIG. 18.—Relations of efficiency 72* to per cent of CO, stack sample (curve No. 1); per cent of CO_2, stack sample (curve No. 2); and per cent of CO_2 (curve No. 3). Tests 89–401.

centage of CO_2 in the furnace and boiler were really about 20 per cent higher on the average than here mentioned because of an air infiltration through the settings amounting to 10 per cent, or 50 per cent of the volume present in the rear of the combustion chamber.

There is a general resemblance between curve No. 3 and the curve in fig. 20 labeled "Heat absorption as affected by combustion-chamber temperature." The latter curve is closely dependent (theoretically) on the CO_2 content, and it probably is no mere coin-

cidence that the two curves have much the same shape. The same remark applies to the analogous curve of fig. 6 (p. 15).

Fig. 21 represents an attempt to find relations between per cent of sulphur in coal (separately determined), per cent of clinker in refuse, and "boiler efficiency" (72*). It is agreed that clinkering is a consequence of the effects of high fuel-bed temperature on such

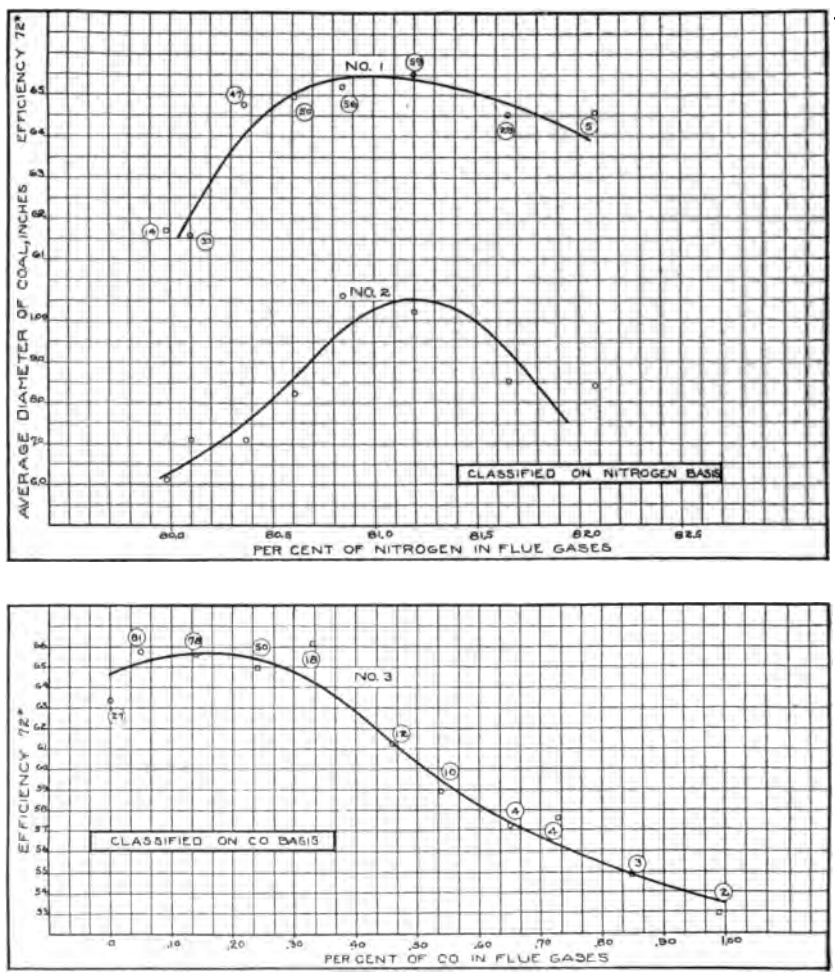

FIG. 19. Relations of nitrogen to efficiency 72* (curve No. 1); nitrogen to average diameter of coal (curve No. 2); and per cent of CO to efficiency 72* (curve No. 3). Tests 89–400.

of the mineral constituents in the ash as will form a fusible mixture. It must be remembered that the fineness of subdivision and the distribution of the minerals throughout the coal are probably as important as the temperature and chemical composition. Thus it is that "sulphur" (pyrites) in the form of little balls is nearly harmless; in the form of veins or layers it is liable to cause trouble; but in the

form of "black sulphur," so finely distributed as to be invisible, it is most troublesome. From these remarks it is evident that the boiler room is not the proper place to make a scientific study of clinkering, but that it should be taken up in the laboratory along the following lines: (1) Ash analyses; (2) experimental determination of fusing points; (3) ascertaining the distribution of the ash and its various constituents throughout the coal.

To determine the fusing point of ash, all the combustible in the ash should be burned out at the lowest possible temperature. The ash could then be made into Seger cones, which could be heated in a furnace and the temperature read with a pyrometer.

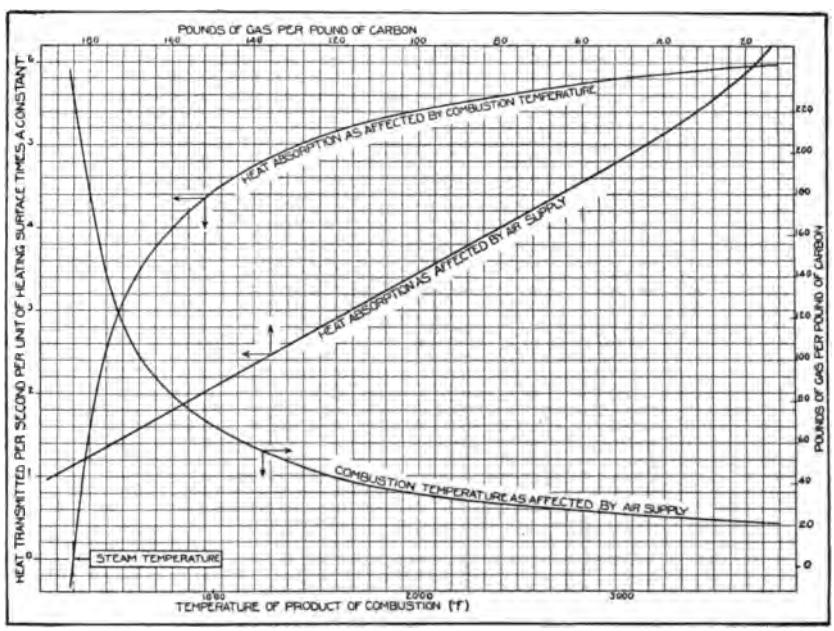

FIG. 20.—Theoretical curves of heat absorption as affected by air supply. Arrows on curves show respective coordinates.

The distribution of the ash might be determined by laboratory washing processes. One method of doing this would be to grind the coal to a certain fineness and float it successively on solutions of potassium hydroxide of varying per cent dilution.

The chemical division, under the guidance of N. W. Lord, is carrying on some of the above investigations, and the writer is indebted to him for explanations of methods.

Notwithstanding the probability, implied above, that sulphur does not have a great deal to do with the formation of clinker, it was thought well to find out whether in general it helps or hinders efficiency.

The upper half of fig. 21 contains tests classified according to "boiler efficiency" (72*). In curve No. 1 each point is the average of the per cent of clinker in refuse for each group and in curve No. 2 of the per cent of sulphur in coal. According to curve No. 1, the coals giving high efficiencies are apt to form a very slightly smaller

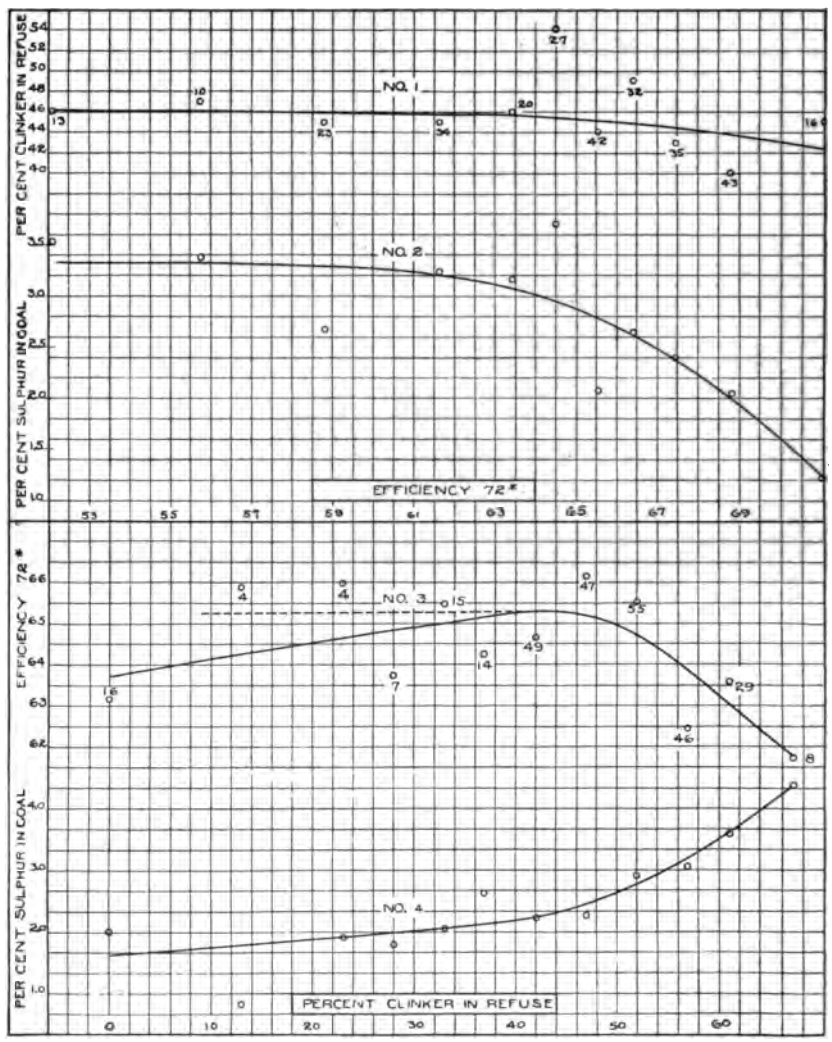

FIG. 21.—Relations of efficiency 72* to per cent of clinker in refuse (curve No. 1); efficiency 72* to per cent of sulphur in coal (curve No. 2); per cent of clinker in refuse to efficiency 72* (curve No. 3); and per cent of clinker in refuse to per cent of sulphur in coal (curve No. 4). Curves Nos. 1 and 2 classified on efficiency 72* basis; Nos. 3 and 4 on clinker basis. Tests 89-401.

percentage of clinker, and according to curve No. 2 the high-efficiency tests are likely to be made on coals low in sulphur, this relation being *rather* marked. However, it must be remembered that high-sulphur *coals are* usually high in ash also.

The indications of the curves of fig. 21, regarding the effect of sulphur, are at slight variance with those of fig. 28 (p. 43).

Careful records were kept regarding the appearance and distribution of the ash of each coal, but time has not been found to study and classify the information.

The lower half of fig. 21 was obtained by classifying the same tests according to the per cent of clinker in the refuse, which was done in order to determine the effect of clinker on efficiency. In curve No. 3 the heavy line gives full weight to 16 tests on coals, some of which were of lignitic character and formed no clinker, but gave rather low efficiencies. Even considering this full portion of the line, instead of the dotted portion above it, the clinker hardly affects efficiency until it reaches about 45 per cent, above which there is a rapid drop. Curve No. 4 indicates that high percentage of clinker accompanies high sulphur content; but it must be borne in mind that perhaps sulphur of itself has little to do with fusibility of ash and that the iron which is combined with a part of the sulphur is only one of the factors in clinkering.

The classification of the relation of efficiency 72* to the sum of the percentages of ash and sulphur, given in the following table, was made by using 92 tests on coals from Illinois, Indiana, and Kentucky, all of which are much alike. To be more certain, the work was done in two ways—by classifying the tests in groups of efficiencies and in groups of percentages of ash plus sulphur. The latter classification is not here given. The tests selected lay between Nos. 126 and 401 and were more comparable than if some earlier ones had been included.

There was no special reason for using the sum of the percentages of ash and sulphur except that it is sometimes stated without qualification that ash and sulphur affect efficiency. The conclusion is that the sum of ash and sulphur has no visible effect on efficiency 72*.

Classification of average ash plus sulphur on basis of efficiency 72 (Indiana, Illinois, and western Kentucky coals).*

	Efficiency 72*.						
	Up to 57.5.	57.5 to 60.0.	60.0 to 62.5	62.5 to 65.0.	65.0 to 67.5.	67.5 to 70.0.	70.0 up.
Number of tests	1	5	8	28	29	17	4
Average efficiency 72*	55.93	58.92	61.39	63.97	66.16	68.50	70.82
Average ash plus sulphur in dry coal	18.89	14.22	15.93	16.65	16.60	15.41	15.86

It was early noticed that the second test on a coal was generally no better as to over-all efficiency than the first. An inspection of the first hundred tests or so confirmed this opinion. Only tests made on the same shipment of the same commercial grade of coal were com-

pared; for instance, if the first test was run on a nut size and the second on screenings, these tests were not used.

It was usually the case that the man running the fire learned much the first day which was beneficial to the later tests, but which was more than offset by other factors. For instance, owing to the position of the chutes that discharge coal into the boiler-room bins and to the sloping bottoms of the bins the largest coal is obtained the first day.

The following tabulation has been made on 196 tests and shows that one test on a coal is sufficient:

Averages of five series of tests for efficiency 72.*

	First tests.	Second tests.	Third tests.	Fourth tests.	Fifth tests.
Number of tests averaged	77	77	32	8	2
Average efficiency 72*	66.05	66.02	65.87	64.99	67.76

The efficiency 72* is that of the furnace and boiler combined, figured from pounds of "combustible" actually ascending from the grate.

MOISTURE IN COAL.

The two curves of fig. 22 are based on the same tests. The upper curve is somewhat misleading, because the poorer coals contained on the average more free moisture. Just what effect different percentages of free moisture would have in the case of the same coal, reckoning above dry coal, is still undetermined. This line of investigation will be taken up in the future. This curve merely indicates that coals high in free moisture should be suspected and watched, especially when burning them in furnaces of this particular type.

The great variability of the lower curve suggests that ordinary percentages of ash have little effect on efficiency, and that the best efficiencies are obtained only with low ash. No doubt other appliances and furnaces are available which would give better results on dirty coal than have been obtained by hand firing on a plain grate.

ASH AND CLINKER.

In order to eliminate one nonuniformity in testing for the effect of percentage of ash in coal as fired on efficiency 72*, only the coals from Illinois, Indiana, and western Kentucky were used. The subjoined table shows that for the range of ash in these coals the efficiency is almost constant.

Fig. 22, in which all the coals tested are classified, shows the effect on efficiency 72* of percentage of ash in coal as fired.

Classification of efficiency 72 on basis of per cent of ash (proximate analysis) in coal as fired (Indiana, Illinois, and western Kentucky coals).*

	Per cent of ash.							
	4 to 6.	6 to 8.	8 to 10.	10 to 12.	12 to 14.	14 to 16.	16 to 18.	18 to 20.
Number of tests	3	10	22	22	19	11	3	2
Average per cent of ash in coal as fired	5.68	7.26	8.99	10.86	13.14	15.11	16.81	18.81
Average efficiency 72*	65.53	65.81	64.02	65.01	65.65	66.08	67.03	65.27

The subjoined table indicates that very few coals burn without clinker. Of the few which do, those high in sulphur are lignites. Pennsylvania No. 7, of test 307, was exposed to weather for four and a half months before it was tested. The same coal when tested

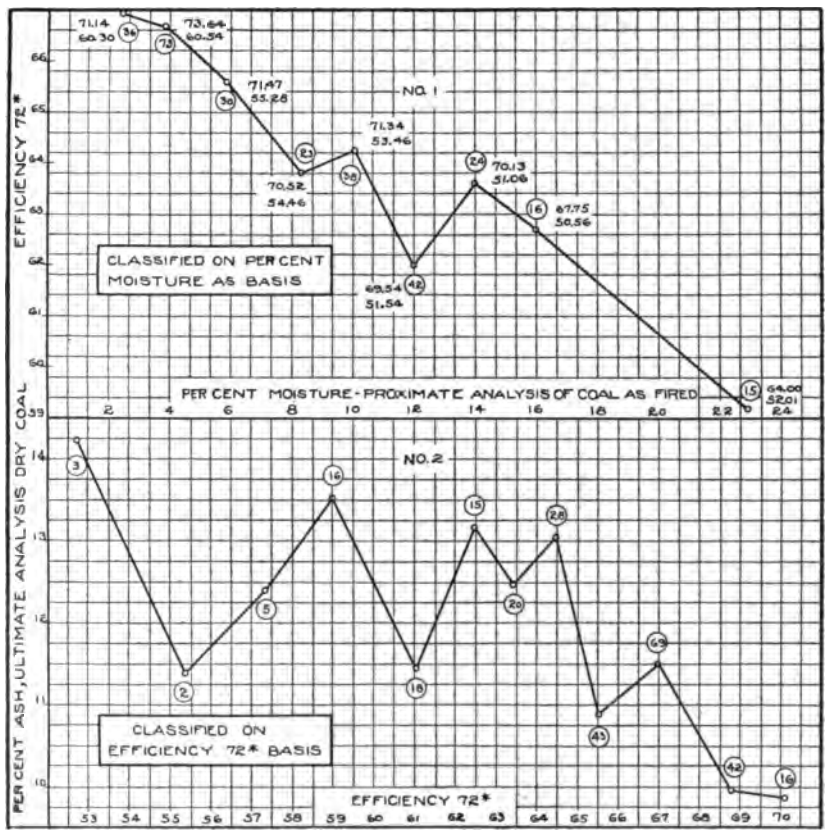

FIG. 22.—Relations of per cent of moisture (proximate analysis) in coal to efficiency 72*, as shown by tests 101–400 (curve No. 1); and of efficiency 72* to per cent of ash (ultimate analysis) in dry coal, as shown by tests 120–400 (curve No. 2).

(test 198) soon after it arrived at the plant formed clinker amounting to more than one-half of the total ash.

The temperatures at which the lignites were burned are rather low, and it is probable that they might have clinkered with high tempera-

tures. The conclusion must not be drawn that some coals represented in this table did not clinker because they were low in sulphur.

Coals burned without producing clinker.

Test No.	Coal.	Combustion-chamber temperature.	Sulphur, separately determined in coal as fired.	Test No.	Coal.	Combustion-chamber temperature.	Sulphur, separately determined in coal as fired.
		°F.	Per cent.			°F.	Per cent.
172	Brazil No. 1	1,900	3.02	387	New Mexico No. 5	2,371	0.81
173	do	1,858	4.53	389	New Mexico No. 3 B	2,225	.74
196	Wyoming No. 2 B	1,950	4.78	391	do	2,432	.69
210	do	2,200	4.37	392	New Mexico No. 3 B (washed)	2,420	.75
213	do	2,142	5.52	396	New Mexico No. 3 A	2,333	.74
290	Washington No. 1 B	2,047	.69	397	New Mexico No. 4 A	2,336	.61
291	Texas No. 4	2,119	.80	398	New Mexico No. 4 A (washed)	2,534	.68
298	do	2,269	.79				
307	Pennsylvania No. 7	2,220	2.36				

The curves of fig. 21 (p. 30) show that the efficiency as based on the coal ascending from the grate (72*) is not influenced by the per cent of clinker in refuse until the latter exceeds 45 per cent, after which the efficiency drops 3 or 4 per cent. Inasmuch as clinker may prevent fine coal from falling through the grate, the same classification was made to learn how per cent of clinker in refuse affected code item 73, which is the over-all efficiency of boiler and grate. This classification is given in the following table. There is only a slight tendency for efficiency to decrease at the high clinker values, whence the deduction can be made that although clinker may hinder combustion it saves almost enough fine coal to compensate for its bad effects. However, it should be noted that the tests showing extremely high clinker were few in number.

Classification of efficiency 73 on basis of per cent of clinker in refuse.

	Per cent of clinker.								
	Under 30.	30 to 35.	35 to 40.	40 to 45.	45 to 50.	50 to 55.	55 to 60.	60 to 65.	65 up.
Number of tests	30	13	12	44	47	55	36	26	7
Average per cent of clinker in refuse	11	33	37	42	47	52	57	61	67
Average efficiency (item 73)	62.95	65.19	63.57	63.96	64.65	64.31	62.95	63.16	62.45

Clinker is an interesting item, as it gets the blame for many things. Figs. 21 and 23 treat some phases of the subject, but the subjoined table has not been plotted.

The impression is general that iron causes clinkering. The tabulation partially confirms the impression, as the percentage of iron in dry coal increases in general with the clinker. Nevertheless iron is only one cause of clinker, and its presence in considerable quantity does not necessarily mean that a coal will clinker.

Classification of per cent of iron on basis of per cent of clinker in refuse.

	Per cent of clinker in refuse.							
	Under 30.	30 to 35.	35 to 40.	40 to 45.	45 to 50.	50 to 55.	55 to 60.	Over 60.
Number of tests	3	5	2	6	14	17	7	5
Average per cent of clinker in refuse	12	32	38	42	47	52	57	63
Average per cent of iron in dry coal	1.01	0.95	1.76	1.54	1.02	1.69	1.81	2.34

The curves of fig. 24 present a classification of tests on the basis of per cent of clinker in refuse. (See also discussion of fig. 28, p. 43.) The table on page 41 was compiled with the object of ascertaining whether any relation exists between the amount of clinker and the

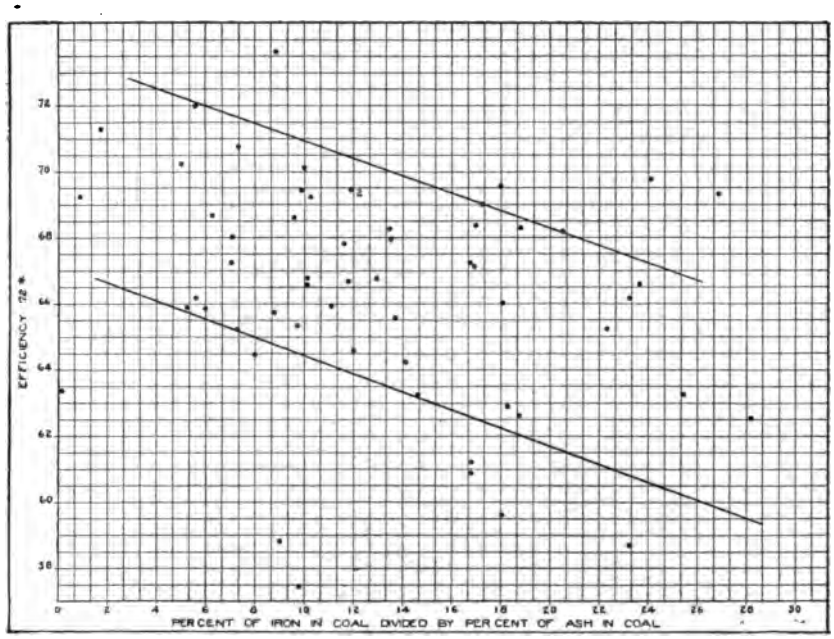

FIG. 23.—Relation between ratio of per cent of iron in coal to per cent of ash in coal (proximate analysis) and boiler efficiency 72*.

average size of the coal and shows that there is very little such relation. One significant feature shown is that the highest value of average size of coal is grouped with the highest value of per cent of clinker, and vice versa.

The curves of fig. 25 show a classification of coals on the basis of carbon-hydrogen ratio. It may be noted that as the per cent of clinker decreases the per cent of CO loss decreases; in fact, the two curves are nearly parallel. The efficiency 72* curve varies inversely with the CO loss and clinker curves. The curve of average diameter on this chart shows that the largest sizes of coal and highest values of clinker are grouped together. The pounds of dry chimney gases per

pound of "combustible" are almost of constant value. This relation is a corroboration of the text relating to fig. 28 (p. 43) regarding incomplete combustion and the decrease of efficiency 72* by the formation of clinker.

It is also likely that although the size of coal burned can not be determined by the amount of clinker formed, it is possible to estimate the amount of clinker that will result from burning different

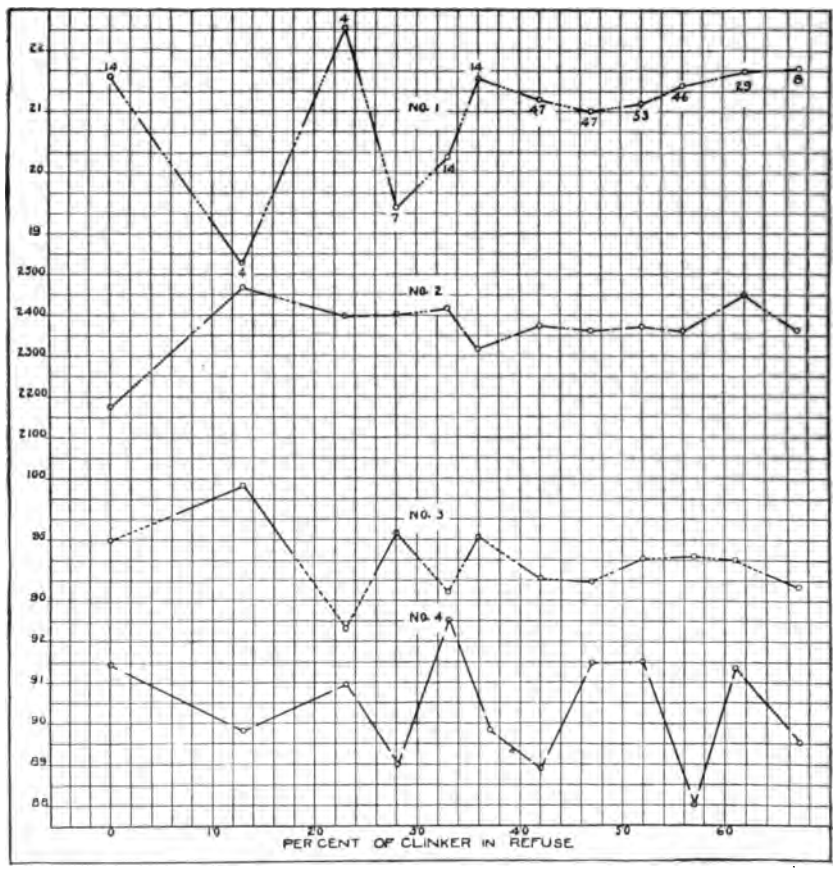

FIG. 24.—Relations of per cent of clinker in refuse to pounds of dry chimney gases per pound of "combustible" (curve No. 1); combustion-chamber temperature (°F.) (curve No. 2); per cent of rated capacity developed (curve No. 3); and per cent of completeness of combustion (E_3) (curve No. 4). Tests 89–400.

sizes of the same kind of coal. With any one kind of coal the amount of clinker formed is related to the distribution and the nature of the ash. Generally the ash is distributed through the coal in thin or thick layers. In coal which is crushed to small sizes these layers become separated from the coal; and when such crushed coal is thrown into the furnace, the particles of ash, being heavier than the coal, soon pass down into the colder layers of ash and fuel near the

grate and are therefore not heated to a temperature high enough to melt. In large-sized coal, on the other hand, the ash remains more in the lumps of coal and is held near the top of the fuel bed, where the temperature is usually above the melting point of the ash.

In plotting the curves of fig. 23 (p. 35) an attempt was made to determine the effect on efficiency 72* of per cent of iron in coal as fired. The ratio of iron in coal to ash in coal was taken as a basis,

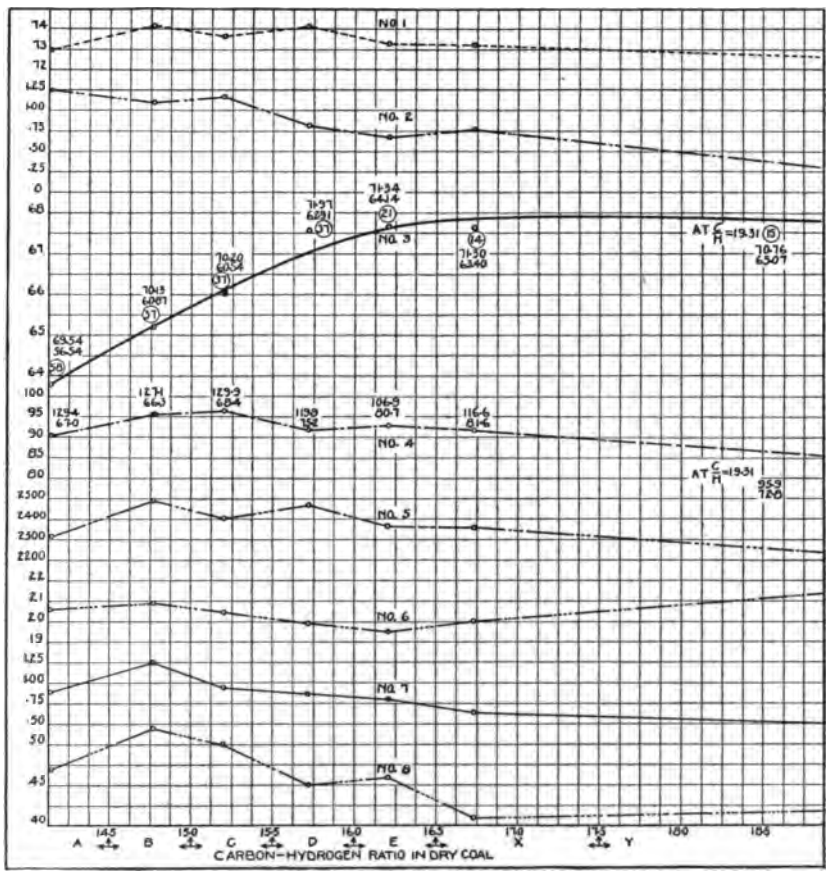

FIG. 25.—Classification based on carbon-hydrogen ratio in dry coal: Curve No. 1, theoretical efficiency of boiler as a heat absorber at various temperatures; No. 2, per cent of CO loss; No. 3, efficiency 72*; No. 4, per cent of rated capacity developed; No. 5, combustion-chamber temperature (°F.); No. 6, pounds of dry chimney gases per pound of "combustible;" No. 7, average diameter of coal; No. 8, per cent of clinker in refuse. Tests 120–380.

because it seemed that there was a close relation between the two; for instance, a large amount of ash and a high iron value would not be expected to cause as much trouble as a high iron value and a low percentage of ash.

Since only about 60 iron determinations were available, it seemed best to plot the individual points instead of average points. The

slope of the band inclosing the points shows that the ratio of iron in coal to ash in coal has perhaps a slight effect on efficiency 72*. This effect is probably due to the formation of nonporous clinker.

The relation of iron in dry coal to clinker in refuse was ascertained by classifying the data on the basis of per cent of clinker, the results showing a large increase in per cent of iron as the per cent of clinker increased. See text relating to figs. 24 and 28 (pp. 43–44) and table on page 35.

L. H. Hartley Smith, writing to Power in 1905, called attention to the fact that the refuse drawn from the ash pit and off the grate when cleaning fires seemed to contain less carbon when the percentage of clinker was high. An inspection of the data of a few of our tests confirmed the observation, and later the following tabulation was made on about 370 tests. The probable explanation is that when clinker forms on the grate it keeps fine coal from falling through.

Classification of per cent of combustible on basis of per cent of clinker in refuse.

	Per cent of clinker.								
	Under 30.	30 to 35	35 to 40.	40 to 45.	45 to 50.	50 to 55.	55 to 60.	60 to 65.	65 up.
Number of tests	38	16	16	56	59	70	59	45	11
Average per cent of clinker	10.9	32.4	37.0	42.1	47.1	52.0	57.6	61.3	66.9
Average per cent of combustible in refuse	25.65	28.29	24.10	23.70	21.75	20.43	18.53	19.40	15.52

Sulphur is an undesirable element in coal. It generally occurs in combination with iron, as iron pyrites, and in combination with calcium, as calcium sulphate or gypsum. Pyrites can readily be recognized by its heavy weight, bright brasslike color, and crystalline structure. The calcium sulphate occurs in small, thin, white flakes, more or less transparent. Of the two sulphur compounds, the pyrites is generally contained in larger quantity in coal, and is harmful because it increases the tendency of the coal to clinker. The clinkering is especially bad if the percentage of ash is small in proportion to the sulphur. In such coals the pyrites and the ash fuse together and form a thin layer of solid clinker, which effectively stops the passage of air through the grate, thereby permitting the grate bars to become heated from the hot fuel bed just above. The clinker then melts down into the spaces between the bars and the sulphur seems to combine with the iron of the grate. The heat warps the grate bars, and the clinker has such corrosive action on the hot iron that a set of grate bars is destroyed in the course of a few days. When such clinkering occurs, any attempt to slice the fire fails, and only slow and very difficult cleaning of the fires will remove the clinkers. Ordinarily, with coals forming loose clinkers, the cleaning of the fires took from seven to twelve minutes.

Virginia No. 4, West Virginia Nos. 14 and 15, and most of the *Kansas* coals clinker badly because the ash is low in proportion to

the sulphur content—0.3 to 6 per cent of sulphur and 3.5 to 10 per cent of ash. When such coals are burned on a plain or a rocking grate trouble with clinkers may generally be prevented by blowing steam under the grate. The usually assigned cause of this effect is that as the steam passes through the hot clinkers it is decomposed into hydrogen and oxygen. This decomposition is a cooling process and the heat needed to effect it is taken from the grate and the hot clinker, thus keeping the latter cool and preventing the fusing of the clinker into the grate.

The use of steam to prevent the clinkers from melting into the grate was found to work satisfactorily with all the coals high in sulphur and ash. However, for coals very low in ash this method sometimes proved to be insufficient. In such cases crushed limestone spread over the thin, clean fire bed immediately on starting the test, prevented the clinkers from adhering to the grate, and was used for the second tests on West Virginia No. 14 and Virginia No. 4 coals. The cleaning of the fires after the first tests on these coals, when limestone was not used, took forty-five and thirty minutes, respectively. On the second tests, when limestone was used, the cleaning took eight and ten minutes, respectively.

To make a general statement, it may be loosely said that the tendency of a coal to clinker varies directly with the sulphur (iron pyrites) and inversely with the ash in the coal.

The statements of this paragraph regarding the effect of sulphur are at slight variance with those on page 34.

The curves of fig. 26 are based on 286 reliable tests, classified according to each of the two items, per cent of ash (ultimate analysis) in dry coal and over-all efficiency (item 73), the latter being the ratio of the heat put into the water to the potential heat in the coal put on the grate. Examination of the upper curve shows that the ash affects the efficiency by only 2 or 3 per cent until the ash content rises above 20 per cent, when the efficiency falls rapidly; however, not so many tests are represented in the last two points of the curve as in the others.

The lower curve shows the same fact inversely—that is, the high-efficiency tests are on coals low in ash. It indicates that an ash increase of 1 per cent causes a drop in efficiency of about 2 per cent, whereas the upper curve indicates a general drop of about 0.5 per cent in efficiency for each per cent of ash, or only one-fourth as much. The average, then, is about 1 per cent decrease in efficiency for 1 per cent increase in ash. The five points at the left end of the lower curve contain tests on clean lignites, and are therefore really not comparable with the other points. These five tests are individually given in the subjoined table.

The two curves show that ash is undesirable; but even so, the commercial choice of coals, so far as ash is concerned, is more a question of market price, freight rates, labor costs, and storage capacity, and of whether or not the present boiler plant is crowded.

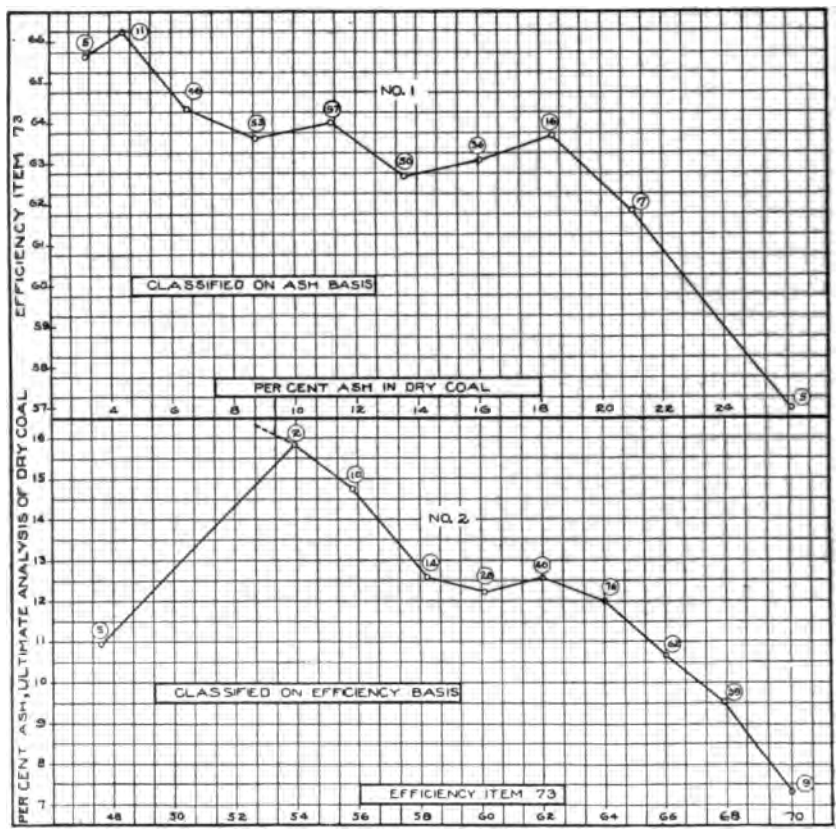

FIG. 26.—Relation of per cent of ash (ultimate analysis) in dry coal to efficiency 73, classified on each as a basis; tests 120–410.

Coals classed in first group of classification on basis of over-all efficiency (item 73).

Test No.	Coal.	Efficiency 73.	Per cent of ash (ultimate analysis) in dry coal.
303	Texas No. 4	49.00	12.95
278	do	51.16	12.86
401	Rhode Island No. 1	49.91	16.87
400	Wyoming No. 6	52.74	5.55
402	Utah No. 2	44.18	6.48

The table which follows shows that size has no evident influence on clinkering, which is the same finding as stated under "Classification on basis of average diameter of coal" (p. 47). These two tables are the converse of each other.

Classification of average diameter of coal on basis of per cent of clinker in refuse.

	Per cent of clinker.										
	Up to 10.	10 to 20.	20 to 25.	25 to 30.	30 to 35.	35 to 40.	40 to 45.	45 to 50.	50 to 55.	55 to 60.	Over 60.
Number of tests	15	4	4	6	14	13	46	43	53	42	28
Average per cent of clinker in refuse	0	13	23	28	33	37	42	47	52	57	62
Average of average diameter of coal, inches.	0.89	0.83	0.50	0.60	0.89	0.85	0.76	0.78	0.83	0.82	1.20

The curves of fig. 27 are plotted from the results of about 300 tests, and differ from those of fig. 26 in being based on the per cent of ash in coal as fired instead of in dry coal. Thus the ash is always less than

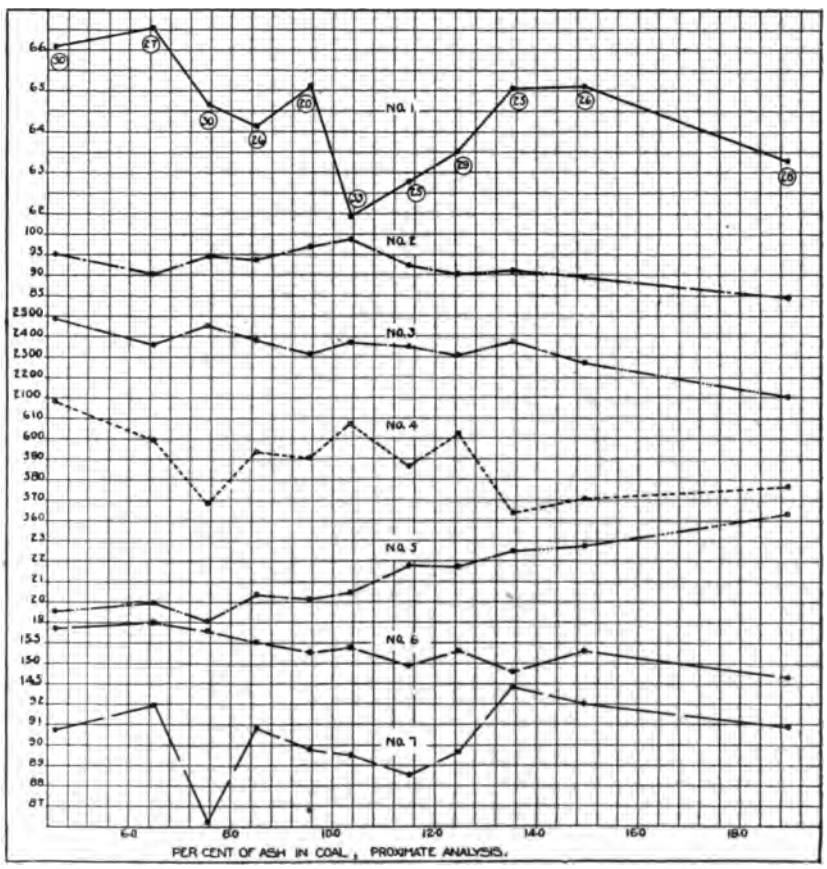

FIG. 27.—Relations of per cent of ash in coal (proximate analysis) to: Efficiency 72* (curve No. 1); per cent of rated capacity developed (curve No. 2); combustion-chamber temperatures (°F.) (curve No. 3); flue-gas temperature (°F.) (curve No. 4); pounds of dry chimney gases per pound of "combustible" (curve No. 5); carbon-hydrogen ratio in dry coal (curve No. 6); and per cent of completeness of combustion (E_3) (curve No. 7). Tests 89–401.

in the dry-coal percentage, but by varying amounts, which perhaps explains the greater irregularity of the code "boiler-efficiency" line (72*), compared with the analogous line of fig. 26, based on over-all

efficiency (code item 73). The tendency of the 72* line to fall is apparent.

A glance at curve No. 2 shows that ash has a worse effect on amount of steam generated, the decrease of which is considerable, than on efficiency.

Curve No. 3, combustion-chamber temperature, shows a steady drop of a few hundred degrees due to increasingly poorer fuel-bed conditions along with falling rates of steam generation.

Curve No. 4, flue-gas temperature, shows a slight drop on account of lower furnace temperatures.

Curve No. 5, the pounds of dry chimney gases per pound of "combustible," shows a marked and steady rise which is the chief reason for the decreasing-furnace and flue-gas temperatures just referred to. It is usually hard to keep the fuel bed in good condition when a coal is high in ash.

Curve No. 6 gives the averages for each group of the ratios of the carbon to the total hydrogen in the dry coal. This line drops, showing that the coals become poorer. The coals in the left-hand groups contain less oxygen in their molecules, so that their hydrogen, though decreasing in percentage, is available in larger amount. The fact that on going to the right the carbon-hydrogen ratio decreases partly accounts for the falling efficiencies shown by curve No. 1. (See p. 68.)

Curve No. 7, per cent of completeness of combustion[a] (E_3), indicates approximately the percentage of total heat liberated from the coal which ascended from the grate. It rises decidedly toward the right in spite of the poorer fuel-bed conditions. The explanation is that inasmuch as the furnace temperature was almost always above the ignition temperatures of all the combustible gases and smoke particles present combustion was retarded more on the left than on the right, because less oxygen was present. For this reason more of the possible heat was generated with the higher ash coals.

It is worthy of note that the high and low efficiencies (72*) in each group (values not shown here) do not vary much between groups. Commercially this similarity of highest efficiencies means that buying coal on the basis of per cent of ash shown by proximate analysis of coal as fired is an uncertain matter so far as obtaining high efficiency thereby is concerned. Classification of the tests made on Illinois, Indiana, and western Kentucky coals on an ash basis shows no more than the minor importance of ash above mentioned.

In making tests on sized coal, as given on pages 45 to 48, there would be an opportunity for research on the question of per cent of ash as affecting the results of boiler trials. Coals of the same size could be classified on the basis of per cent of ash and the effect of the ash thus studied separately from the effect of size. It does not seem, how-

[a] See glossary (p. 181), under "Efficiencies."

ever, that for the range of per cent of ash found in coal this investigation would be important, for it is not the amount of ash, but its composition and distribution, that affects the results of a steaming test.

With a knowledge of ash composition it could be decided how the coal was to be burned. For instance, a coal which did not clinker badly, but which burned leaving free ash, would be burned under ideal conditions on a rocking grate no matter how high the per cent of ash. A coal which clinkered badly at high temperatures should

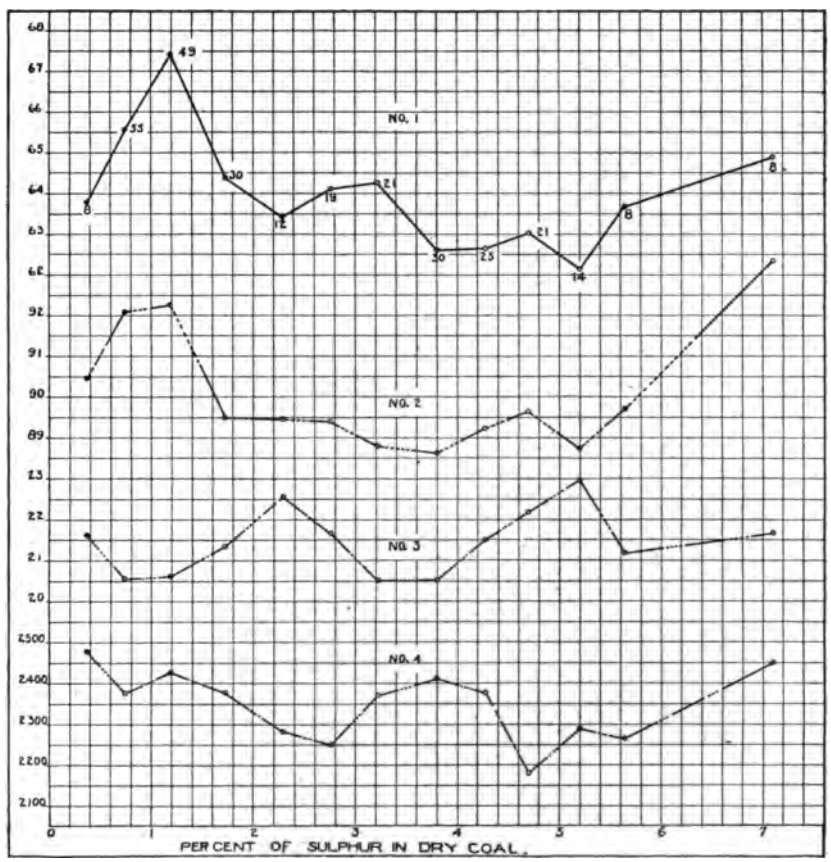

FIG. 28.—Relations of per cent of sulphur in coal to boiler efficiency 72* (curve No. 1); per cent of completeness of combustion (E_3) (curve No. 2); pounds of dry chimney gases per pound of "combustible" (curve No. 3); and combustion-chamber temperature (°F.) (curve No. 4) Tests 89–400.

be gasified at a low temperature, thereby avoiding an amount of clinkering that would stop up the air passages and also preventing clinkers from adhering to the grate. It is a study of ash composition along with the manner of distribution of the ash in the coal that is needed.

The curves of fig. 28 present a classification based on per cent of sulphur in dry coal. For the low sulphur values there is a wide variation in efficiency 72*. As the per cent of sulphur increases, up

to 5 per cent, there is a gradual drop in efficiency 72*. There were 16 tests in which the per cent of sulphur was over 5.4. At the high values of sulphur the efficiency 72* curve rises, probably because the sulphur is in different form and also differently distributed. A curve through the average efficiency points shows a drop of 5 per cent, with an increase of 5 per cent in the sulphur, or, in other words, every increase in the per cent of sulphur in dry coal decreases the efficiency in equal amount.

Curve No. 2 shows the per cent of completeness of combustion (E_3), and is nearly parallel to the efficiency 72* curve.

Curve No. 3 shows the pounds of dry chimney gases per pound of "combustible," and rises slightly with the per cent of sulphur.

Curve No. 4 shows the combustion-chamber temperature, which, except for the high sulphur values, decreases as the per cent of sulphur increases, indicating a value at the high sulphur values about 300° F. higher than an average curve through the combustion-chamber temperature points would indicate that it should be. The curves of fig. 17 (p. 25) show that this increase of temperature nearly accounts for the increase of efficiency 72* at the high sulphur values.

The curves of fig. 21 (p. 30) show that as the per cent of clinker in the refuse increases the per cent of sulphur increases; also that all the highest values for per cent of clinker are grouped with the higher values for per cent of sulphur. The low per cent of values for sulphur are grouped with the high values for per cent of efficiency 72*, and vice versa. At the highest values for per cent of clinker the efficiency 72* is lowest, and with high efficiency 72* the per cent of clinker is the lowest. This relation was determined from two different classifications—one on per cent of clinker in refuse and one on efficiency 72*. The classification on per cent of clinker in refuse shows that efficiency 72* is more influenced by per cent of clinker than the per cent of clinker is influenced by this efficiency. The latter influence was determined by classifying on an efficiency 72* basis.

On referring to fig. 24 (p. 36), a classification on the basis of per cent of clinker in refuse, it is to be noted that for all values of per cent of clinker the combustion-chamber temperature and pounds of dry chimney gases are about constant.

The general conclusion is that the per cent of sulphur does affect efficiency 72* indirectly by the formation of clinker. Since the amount of air used is a constant value, it is quite possible that the decreasing value of efficiency 72* with increasing per cent of sulphur is due to the effect of clinker on the distribution of the air supply. Moreover, with the high values for per cent of clinker probably more of the air enters the furnace over the fire.

AVERAGE DIAMETER OF COAL.

Preliminary to the discussion of the results produced by using coal of different sizes it may be of value to state how the coal is received at the fuel-testing plant and how the size is determined, and to suggest how further research work might be done on the influence of size.

Nearly all of the coal tested was passed through a crusher, and consequently coals of widely varying characteristics were reduced to the same size. Therefore by classifying coals on a size basis, as we have done, we have averaged a good eastern coal with a poor-grade western coal. While size shows, on the average, some few general relations, it would seem that the best comparable data could be obtained by taking one coal, say, run of mine, and after separating the various sizes, making a series of tests on each size. Even such tests would not be made on the same grade of coal, as the smaller sizes are sure to be higher in ash; but nevertheless this side of the problem is of commercial importance.

After the sample of the coal tested has been quartered and a part sent to the chemist for analysis, the remainder is passed through a revolving screen perforated its entire length with round holes ranging from one-eighth to 1 inch in diameter. These holes are arranged in strips or sets of rows, the width of which decreases as the size of hole increases. The coal passing through each set of holes is weighed separately and the data from the boiler room are reported, as follows:

Determination of average diameter of coal samples.

Diameter of holes (inches).	Pounds of coal through each set of holes.		Weight of coal, determining average size.
	Actual.	Reduced to 100-pound basis.	
1.	2.	3.	4.
⅛	20	20.4	2.6
¼	14	14.3	3.6
⅜	18	18.4	6.9
½	12	12.2	6.1
¾	27	27.6	20.7
1	4	4.1	4.1
1½	3	3.0	4.5
	98	100.0	$\frac{48.5}{100.0}=0.49$

Column 2 shows that 98 pounds of coal was sized. No attempt is ever made to weigh out exactly 100 pounds, so the weights must be reduced to 100, as has been done in column 3, thereby obtaining the percentages of the various sizes of coal. From the construction of the revolving screen it follows that in an average diameter each of the percentages has a "weight of observation" proportional to the

diameter which it represents. In getting average diameter, then, column 3 is multiplied by column 1, obtaining column 4, and the sum of this column of products divided by 100, therefore, gives the weighted average size of the coal.

The classification plotted in the curves of fig. 29 was made on the coals tested in tests 89 to 401, and shows that as the average diameter increased from 0.35 to 1.26 inches (1) the capacity increased about 15

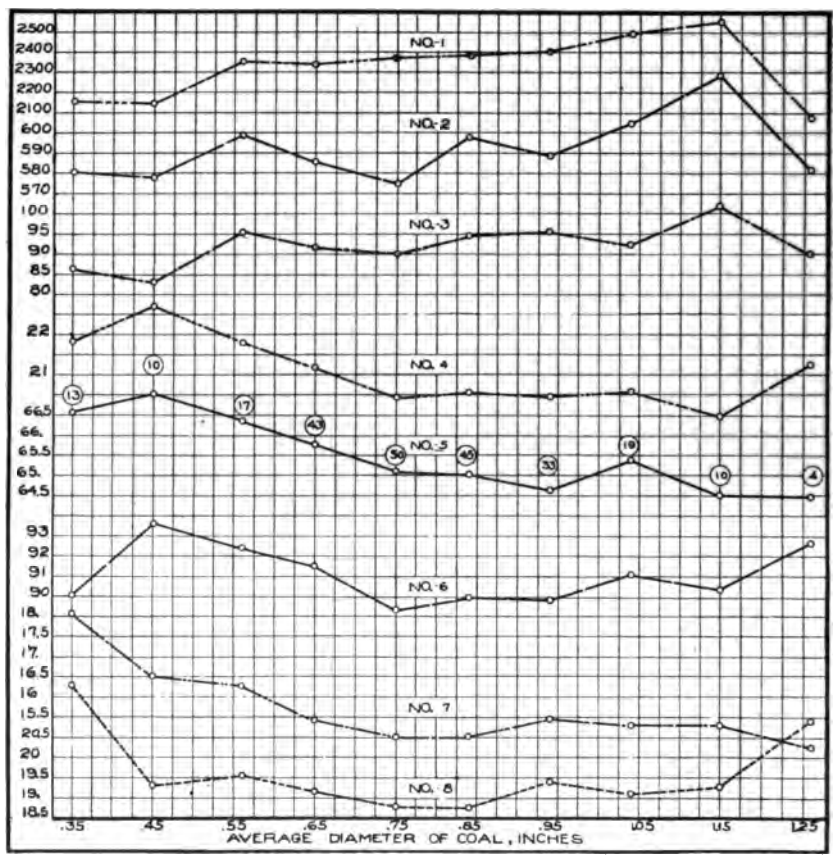

FIG. 29.—Relations of size of coal to combustion-chamber temperature (°F.) (curve No. 1); flue-gas temperature (°F.) (curve No. 2); per cent of rated capacity developed (curve No. 3); pounds of dry chimney gases per pound of "combustible" (curve No. 4); efficiency 72* (curve No. 5); per cent of completeness of combustion (E_3) (curve No. 6); carbon-hydrogen ratio in dry coal (curve No. 7); and ratio of carbon to available hydrogen (curve No. 8). Tests 89–401.

per cent (curve No. 3); (2) the highest efficiency 72* values were obtained with the smallest sizes (curve No. 5); (3) there was practically no change in the per cent of completeness of combustion (curve No. 6); (4) there was a slight decrease in the pounds of dry chimney gases per pound of "combustible" (curve No. 4); and (5) the carbon-hydrogen ratio figured from the dry coal decreased considerably (curve No. 7), showing that the good coals fall in the groups of small-

est average diameter, this result being probably due to the fact that some of the good coals broke up badly in transportation and in passing through the crusher; (6) the combustion-chamber temperature increased about 400° F. (curve No. 1).

It should be borne in mind in considering these general results, which are so different from the usual conclusions, that they are only tentative, because other conditions varied so widely. The study of effect of size as above outlined is not specialized enough, for undoubtedly other factors than average size are influential—e. g., perhaps, percentage of voids, as dependent on percentage of various sizes forming average diameter, shape of pieces, etc.

In discussing the effect of average size of coal as based on these tests it is well to remember that none of the coal is really fine, for the lowest sizes averaged about 0.3 inch. On the other hand, the largest sizes averaged only 1.25 inches.

The tabulation headed "Classification of per cent of clinker on basis of average diameter of coal," which follows, was made to ascertain whether the size of coal had any influence on its tendency to clinker. About 300 tests were used, but they were on all kinds of coal, from all parts of the country, and no such influence is indicated. (See "Classification on basis of per cent of clinker in refuse," p. 41.)

Classification of per cent of clinker in refuse on basis of average diameter of coal.

	Average diameter (inches).									
	Below 0.40.	0.40 to 0.50.	0.50 to 0.60.	0.60 to 0.70.	0.70 to 0.80.	0.80 to 0.90.	0.90 to 1.00.	1.00 to 1.10.	1.10 to 1.20.	Over 1.20.
Number of tests	15	16	19	41	51	45	33	19	8	21
Average diameter of coal (inches)	0.35	0.44	0.56	0.65	0.75	0.84	0.94	1.04	1.14	1.25
Average per cent of clinker in refuse	44	46	35	43	46	47	50	46	34	45

Fig. 30 shows some of the many variations encountered when making sizing tests. The seven tests from which this chart was plotted were made on mixed bituminous coals, made up of several of the officially numbered coals, and accurately sized by passing through a revolving screen. The per cent of sulphur and per cent of moisture were about constant in the mixtures. The fact that the carbon-hydrogen ratio of the dry coal used decreased as the coal became larger (curve No. 1) seems to indicate that the tests were not run on uniform mixtures of coals; perhaps certain coals were finer or coarser than others before mixing. The coals were accidentally mixed in a general heap, in consequence of a fire in the washer plant, and it was not known just what they consisted of except that they came from the so-called Illinois and Missouri coal basins.

A significant fact brought out by the chart is that the efficiency 72* was about constant for all the sizes.

Certain values varied as the size of the coal increased. Curve No. 1 shows that the carbon-hydrogen ratio in dry coal decreased, and thereby tended to lower efficiency 72*. Curve No. 2 shows a slight rise of efficiency 72*. Curve No. 3 shows a steady increase in the difference between the draft in the stack and that over the fire, for which no explanation is offered. Curve No. 4 shows an irregular but decided increase in pounds of coal burned per square foot of grate per hour—a

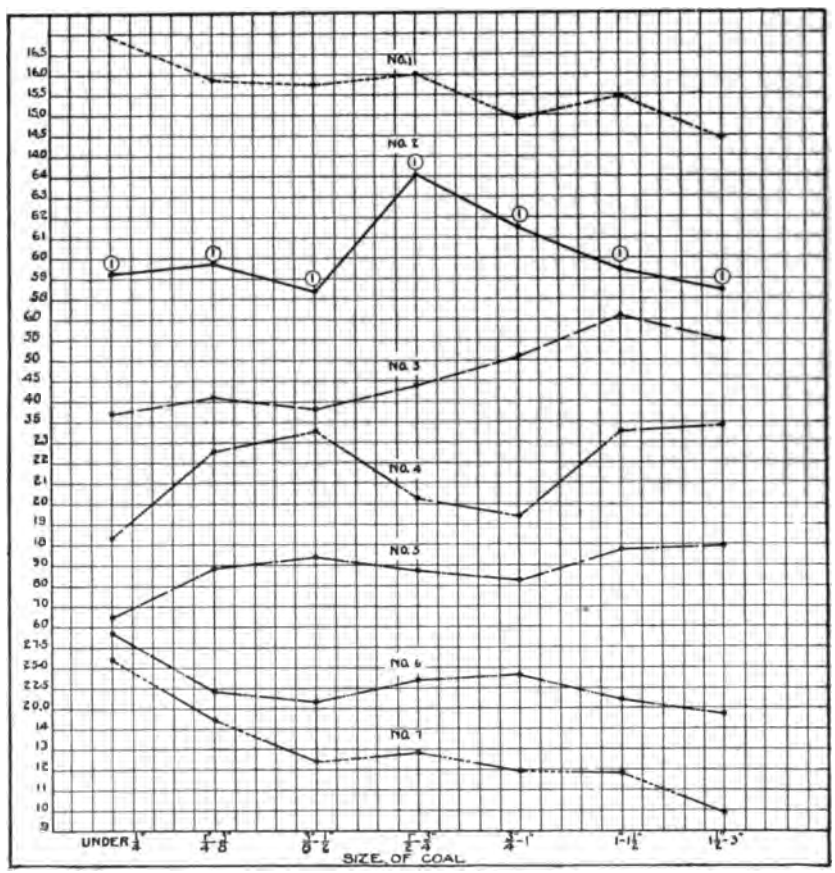

FIG. 30.—Relations developed on accurately sizing mixed bituminous coal: Curve No. 1, carbon-hydrogen ratio in dry coal; No. 2, efficiency 72*; No. 3, difference between draft in stack and draft over fire; No. 4, pounds of dry coal burned per square foot of grate surface per hour; No. 5, per cent of rated capacity developed; No. 6, pounds of dry chimney gases per pound of "combustible;" No. 7, per cent of ash in coal (proximate analysis).

direct consequence of the increase in size of the coal. It should be borne in mind that the stack draft available was always about the same. Curve No. 5 is of the same shape in detail as No. 4, and shows an increase in the rate of steam production. Curve No. 6 is practically level, except at the left end, where it is high—perhaps because *the coal* was so fine that it caked and allowed cracks to form in the

fuel bed, or because the ash contained was high. Curve No. 7 shows that much of the ash went into the fine coal. It is worthy of remark that the finer and dirtier sizes gave nearly as high efficiency as the larger sizes.

The sole advantage of the larger sizes of coal over the smaller, so far as shown by these few tests, was that a higher rate of steam production was attained.

An attempt was made to determine the effect of ⅛-inch size (in Indiana, Illinois, and western Kentucky coals) on efficiency 72*, per cent of CO loss, and combustion-chamber temperature; but the results were negative, and emphasize the statements made on page 47, that the study of the effects of the various elements of size of coal has not been made in sufficient detail. It is also likely that the effects of size are obscured greatly by other factors, such as caking, moisture, etc. The following table of results does not seem to indicate much:

Classification of efficiency 72, per cent of CO in flue gas, and combustion-chamber temperature on basis of per cent of ⅛-inch coal (Illinois, Indiana, and western Kentucky coals).*

	Per cent of ⅛-inch coal.						
	0 to 5.	5 to 10.	10 to 12.	12 to 14.	14 to 16.	16 to 17.	17 to 18.
Number of tests[a]	4	13	9	4	4	7	7
Average per cent of ⅛-inch coal	4.0	8.2	11.1	12.2	14.9	16.2	17.6
Average efficiency 72*	65.02	63.74	66.18	68.05	65.57	65.88	63.88
Average per cent of CO in flue gas	0.11	0.27	0.19	0.19	0.30	0.18	0.17
Number of tests[a]	3	8	7	3	2	6	2
Average combustion-chamber temperature (° F.)	2,612	2,483	2,367	2,302	2,240	2,370	2,393

	Per cent of ⅛-inch coal.					
	18 to 19.	19 to 21.	21 to 23.	23 to 25.	25 to 30.	30 to 40.
Number of tests[a]	4	9	6	6	6	5
Average per cent of ⅛-inch coal	18.4	19.9	22.0	24.0	26.2	32.7
Average efficiency 72*	66.74	64.98	65.84	65.92	66.67	65.84
Average per cent of CO in flue gas	0.24	0.26	0.16	0.13	0.14	0.27
Number of tests[a]	2	4	3	5	4	4
Average combustion-chamber temperature (° F.)	2,371	2,299	2,104	2,245	2,245	2,378

[a] Fewer tests were used to obtain the average combustion-chamber temperature than for the other averages, owing to the fact that the questionable results were eliminated.

The coals used for sizing came from Illinois, Indiana, and western Kentucky. Not many tests are used here and the results would not be expected to convey much information even had the coals come from one locality; because, for example, from the State of Illinois it is possible to obtain about as good and as poor bituminous coal as is mined. The results, given in the table on the following page, show a small increase in efficiency 72* and a large increase in combustion-chamber temperature as the size of coal increases.

Classification of efficiency 72, per cent of CO in flue gas, and combustion-chamber temperature on basis of average diameter of coal (Illinois, Indiana, and western Kentucky coals).*

	Average diameter (inches).							
	Up to 0.5.	0.5 to 0.6.	0.6 to 0.7.	0.7 to 0.8.	0.8 to 0.9.	0.9 to 1.0.	1.0 to 1.2.	1.2 up.
Number of tests [a]	9	4	16	22	15	7	3	8
Averages of average diameter (inches)	0.39	0.58	0.66	0.74	0.83	0.95	1.04	2.51
Average efficiency 72*	64.83	67.69	65.75	65.19	65.00	66.88	68.50	63.68
Average per cent of CO in flue gas	0.18	0.31	0.16	0.23	0.20	0.34	0.15	0.11
Number of tests [a]	7	2	7	14	11	5	3	4
Average combustion-chamber temperature (° F.)	2,080	2,406	2,258	2,357	2,405	2,412	2,542	2,576

[a] Fewer tests were used to obtain the average combustion-chamber temperature than for the other averages, owing to the fact that the questionable results were eliminated.

Increasing the size of fuel by briquetting would seem from theoretical reasoning to be a move in the wrong direction. Other things being equal, it is self-evident that the more nearly the size of a particle of coal approaches that of an atom the better, for then each particle will burn instantly on coming in contact with two atoms of oxygen. It is also self-evident that the smaller the individual particles of coal put into a furnace or gas producer the less will be the protecting effect of the surface coating of ash formed by the burning away of the outer portions of the grains. From a mathematical standpoint it can be seen that the volume of a body increases proportionately to the cube of its diameter, but the exposed surface increases only as the square of its diameter, and in combustion it is exposed surface that counts for rapidity. Therefore, to repeat, it would seem that on this basis alone, artificially increasing the size of fuels is, to speak generally, working in the wrong direction. It is recognized that improved results are obtained by briquetting some fuels, but that probably still better results can and will be obtained in the future by devising furnaces and gas producers of such types as will utilize fine coal better than coarse. So far the only step made in this direction has been the burning of pulverized coal in furnaces. Perhaps the slowness of development in this field is attributable to the expense of grinding the coal, which has never had a fair trial on a large scale, and also indirectly to the softening of the fire-brick lining due to the fact that pulverized-coal furnaces are customarily run too hot. The work done by the boiler division, and set forth on pages 20, 23, 56, shows the error of the general impression that very high furnace temperatures are necessary for very high over-all efficiencies. Viewed from this standpoint, it is not improbable that in the future the burning of fine and pulverized coal, perhaps even without extreme pulverization, will increase largely. In cement kilns, for instance, such coal has been a great success for the reason that the lining of the kiln is protected by the material itself which it is desired to melt. One reason for the nonutilization of slack coal is because too little attention has been given to this general subject.

As indicating a right trend in this matter, attention may be called to the success of the large power houses of the country in burning fine coals, which a few years ago were used as railroad ballast or thrown on dump heaps. The over-all efficiencies are in many cases quite equal to those which could have been obtained with the stokers and grates of a few years ago when using cleaner coals of larger and more uniform size. Perhaps in a few more years no complaint will be heard against fine coal. Every engineer knows that, whereas egg and lump coal used to be sought after, the large power houses now put all their coal through crushers which reduce it to a size which a few years ago would have been thought almost useless.

PER CENT OF RATED CAPACITY DEVELOPED.

No attempt is made here to discuss in detail the causes of the showing of the following table, which is one of the most significant in this volume. It indicates that for every capacity group the "boiler efficiency" (72*) is independent of the combustion-chamber tem-

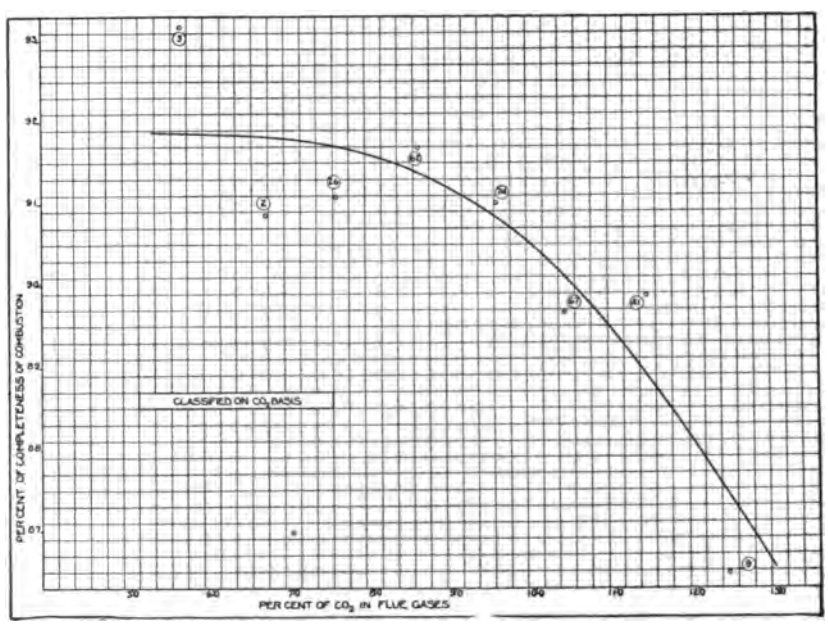

FIG. 31.—Relation of per cent of CO_2 in flue gases to per cent of completeness of combustion (E_2), tests 89–401.

perature and practically constant throughout the whole range of temperature. The suggested explanation is that as the temperature of combustion rises the oxygen content of the gases decreases, which reduces the completeness of combustion sufficiently (see figs. 13, p. 22; 14, p. 23; and 31) to neutralize the slight rise of boiler efficiency due to higher initial temperatures. This same result is shown for all tests grouped with regard to amount of coal burned (figs. 12, p. 21, and 17, p. 25).

Classification of combustion-chamber temperature and efficiency 72 on basis of per cent of rated capacity developed.*

Per cent of rated capacity developed.											
70 to 75.			75 to 80.			80 to 85.			85 to 90.		
Combustion-chamber temperature (°F.).	Number of tests.	Efficiency 72*.	Combustion-chamber temperature (°F.).	Number of tests.	Efficiency 72*.	Combustion-chamber temperature (°F.).	Number of tests.	Efficiency 72*.	Combustion-chamber temperature (°F.).	Number of tests.	Efficiency 72*.
1,870	1	66.38	1,880	1	60.89	1,961	1	67.64	2,067	6	65.93
1,936	2	64.07	1,967	2	59.79	2,046	4	62.33	2,140	2	64.56
2,253	1	65.04	2,039	3	66.35	2,163	3	67.68	2,231	9	66.13
			2,118	1	65.95	2,259	11	65.79	2,354	8	64.83
			2,247	1	68.54	2,325	5	67.39	2,421	5	65.79
			2,350	2	63.68	2,419	5	66.87	2,525	1	65.25
						2,597	1	66.82	2,672	2	65.94
		[a] 64.89			[a] 64.12			[a] 66.06			[a] 65.59

Per cent of rated capacity developed.											
90 to 95.			95 to 100.			100 to 105.			105 to 110.		
Combustion-chamber temperature (°F.).	Number of tests.	Efficiency 72*.	Combustion-chamber temperature (°F.).	Number of tests.	Efficiency 72*.	Combustion-chamber temperature (°F.).	Number of tests.	Efficiency 72*.	Combustion-chamber temperature (°F.).	Number of tests.	Efficiency 72*.
2,050	2	67.46	2,248	6	67.32	2,256	2	65.09	2,290	3	66.19
2,178	2	65.88	2,368	7	65.63	2,327	3	66.46	2,345	3	67.44
2,244	3	69.23	2,457	11	65.83	2,474	4	67.55	2,448	9	65.03
2,359	12	65.45	2,554	6	64.88	2,550	5	66.10	2,534	1	65.83
2,456	8	65.88	2,627	2	65.80	2,660	1	65.22	2,653	5	65.01
2,546	5	69.41	2,722	1	68.06	2,839	2	66.55	2,708	1	64.61
2,637	1	68.61							2,864	1	73.64
2,708	1	64.97									
		[a] 66.60			[a] 65.95			[a] 66.38			[a] 65.88

[a] Average.

PYROMETRY.

For measuring the furnace and the combustion-chamber temperatures, both a Wanner optical pyrometer and a thermoelectric couple of platinum and platinum rhodium were used.

The Wanner optical pyrometer (fig. 10, p. 19) was the more reliable and by far the more convenient to use. The working of this instrument is based on the relation which exists between the temperature of a hot body and the intensity of the light which it emits.[a] The instrument itself makes use of an incandescent lamp which is

[a] For the theoretical discussion of this subject see Waidner, C. W., and Burgess, G. K., Optical pyrometry: Bull. No. 2, Bureau of Standards, U. S. Dept. Commerce and Labor.

standardized by comparison with an amyl-acetate standard lamp, and consists of a photometer for comparing the light emitted by the body whose temperature is to be measured with a steady light of known intensity. The comparison light is a 6-volt incandescent lamp, supplied by a storage battery, illuminating a ground-glass surface. A beam of monochromatic (red) light from this source—produced by means of a direct-vision spectroscope and a screen, cutting out all but a narrow band in the red—and a similar beam from the hot body are passed into a photometric telescope, each beam illuminating one-half of the telescopic field. The photometric comparison is made by adjusting to equal brightness both halves of the telescopic field by means of a polarizing arrangement.

One of the advantages of the optical pyrometer is that it is more apt to take the average temperature of a strip across the furnace from wall to wall. Furthermore, it gives temperature changes instantaneously and in absolute measure, which, even in case the flames appear hotter than they really are, can hardly be in error more than 150° F. This error is probably more than offset by the fact that the furnace is not a perfect "black body."

The most serious source of error, except when special precautions are taken, is the variation in brightness of the electric comparison lamp due to variation in the current furnished by the three-cell storage battery, the percentage of change in light being of the order of six times the percentage of change in current through the lamp. Breaking the circuit and then making it again may cause an apparent change of more than 20° C. It has been found that for a series of observations lasting from one-half hour to two hours it is better to take all readings, after once standardizing the instrument, without breaking the lamp circuit, instead of breaking it after every single reading.

Before standardizing the instrument the amyl-acetate standard lamp should be allowed to burn from five to ten minutes to get a steady flame. To supply the incandescent lamp a 20-ampere-hour storage battery was used for most of the readings recorded in this work.

The thermoelectric couple used for pyrometric tests was connected either to a millivoltmeter equipped with a scale of temperatures or to a Callendar recording instrument. There were two of the latter instruments; one was to be used with the thermoelectric-couple pyrometer and the other with an electric-resistance pyrometer. Owing to the fact that these pyrometers, as sold, do not stand the furnace temperatures for any great length of time there was no opportunity to give the recording instruments a fair trial, and therefore they are not considered in detail in this report.

The thermoelectric couple as it came from the maker consisted of a platinum and platinum-rhodium junction inclosed in a porcelain tube of $\frac{3}{8}$-inch bore and $\frac{5}{8}$-inch outside diameter. However, this porcelain tube could not stand the high temperature, and particularly the slagging action of the furnace gases. The slag accumulated on the surface of the tube and seemed to change the composition of the porcelain. The tube partly melted, and then, after it had been in the combustion chamber for two hours, broke off, although there was nothing in the chamber to strike it. A water-jacketed iron pipe, similar to the gas sampler shown in fig. 15 (p. 24), was tried instead of the porcelain tube, the two wires being insulated from each other and from the pipe by pieces of small glass tubing. The thermoelectric junction projected 3 inches from the end of the iron pipe, and was held in two stems of penny clay pipes. This arrangement lasted over a week in the combustion chamber and gave fairly satisfactory results. During this time the couple was continually connected to the Callendar recording instrument.

The records obtained with the thermoelectric apparatus had a value only so far as the relative temperatures were concerned. For absolute temperature the apparatus could not be depended on, because it was impossible to apply any scale or rule to the record when the mass around the junction of the couple was one fused mass of slag. It was also found that the variations in temperature shown by this couple were lagging from six to eight minutes. A couple fitted with a water-jacketed iron pipe had to be rigidly connected to a water supply. On that account such an arrangement could not be used for measuring temperatures in different parts of the furnace, and for this purpose a plain $\frac{1}{2}$-inch iron pipe was used. The junction of the wires was, as before, held in two clay pipestems, which projected about 2 inches from the end of the iron pipe. Clay pipestems had to be used also for insulating the wires inside of the iron pipe for a length of about a foot back from the end, on account of the high temperature to which the end was subjected. Even with this special arrangement the thermoelectric couple could be exposed to the high temperature of the furnace only long enough to get the projecting junction hot and take the reading. This exposure usually lasted fifteen to twenty seconds, after which the instrument had to be withdrawn and cooled off. Even with this care the iron pipe lasted for only thirty to fifty single readings, after which it became so burned that it had to be replaced by a new one. This instrument also could be depended on only for relative temperatures in different parts of the furnace.

After all the difficulties that are encountered in using a thermoelectric couple for measuring furnace temperatures, this apparatus measures only the temperature of a very small part of the furnace,

where the instrument is inserted, and the temperature midway between the side walls may be much higher than it is at points reached by the couple, 8 inches from the walls.

Fig. 32 gives a comparison of the combustion-chamber temperatures taken with the Wanner optical pyrometer with the rise in temperature of water from a water-jacketed gas sampler inserted in the rear of the combustion chamber. A mercury thermometer was inserted

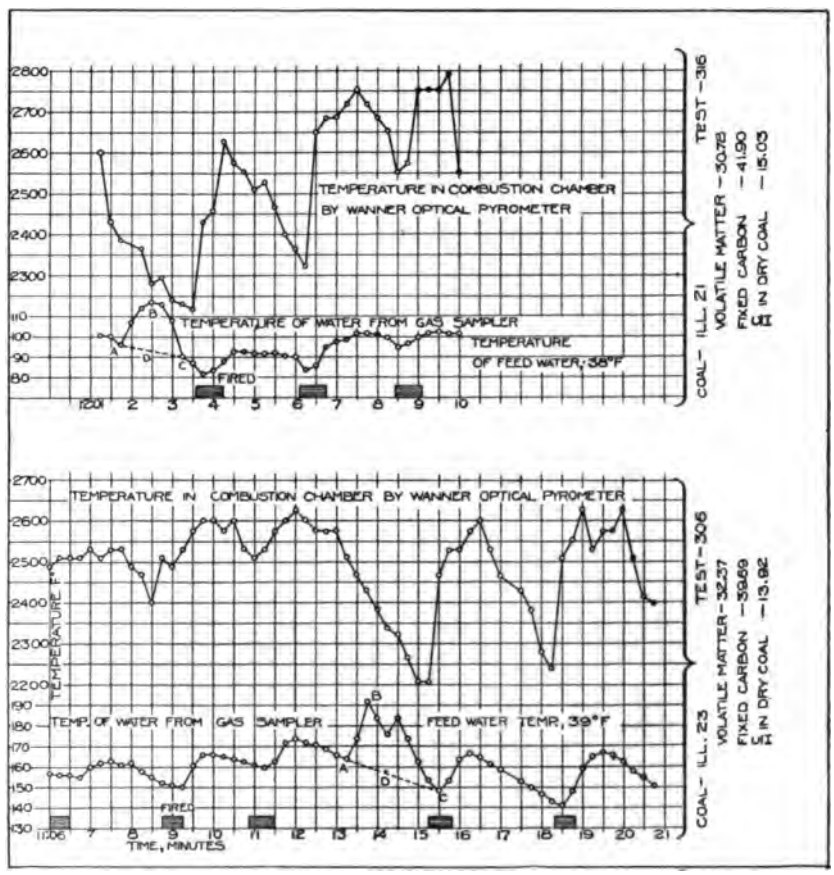

FIG. 32.—Comparison of Wanner optical pyrometer temperatures in combustion chamber with rise in temperature of water from a jacketed gas sampler.

into the water outlet of the gas sampler and was read simultaneously with the optical pyrometer. The two curves agree very well, the temperature of the water lagging slightly. The elevation of temperature at A, B, C in the water-temperature curve is due to reduction of pressure in the water main caused by the taking of water into the measuring tanks for feeding the boiler. But for this circumstance the curve would run as shown by the dotted lines A, D, C.

SMOKE.

The curves of fig. 33 are plotted on the basis of per cent of black smoke. Curve No. 1 indicates that the efficiency 72* rises a little more than 1 per cent until about 20 per cent of black smoke is reached, and then gradually drops. This drop in efficiency amounts to about 2.5 per cent within the range of 20 to 50 per cent of black smoke. The drop in efficiency when there is little or no smoke can be explained by noting that a greater amount of air was used for combustion of

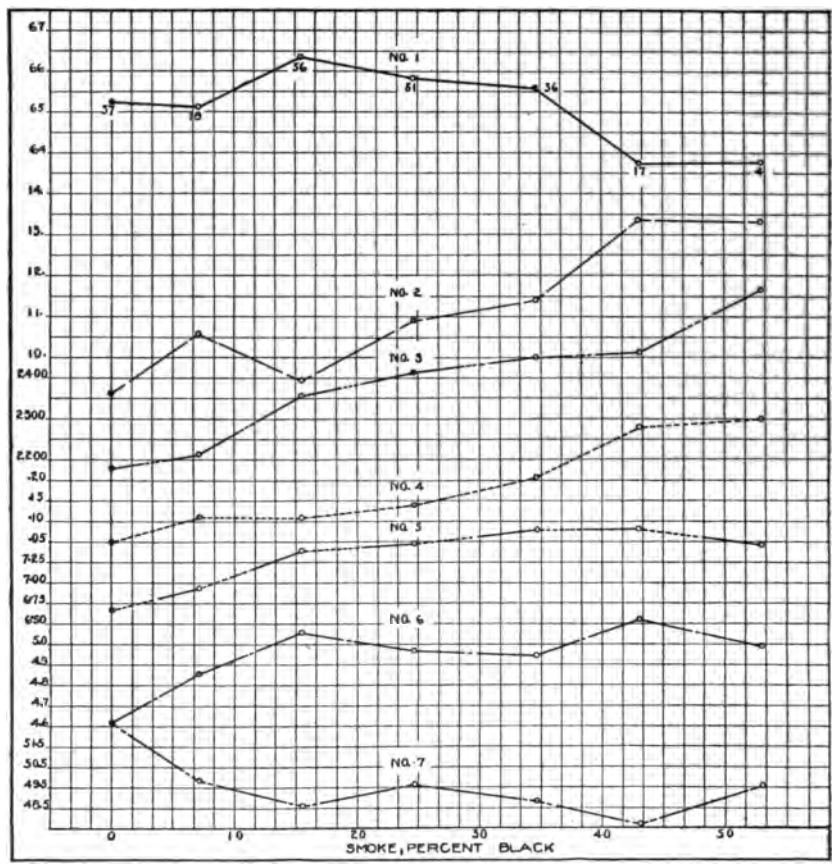

FIG. 33.—Relations of smoke per cent to boiler efficiency 72* (curve No. 1); per cent of unaccounted for loss taken from heat balance (curve No. 2); combustion-chamber temperature (°F.) (curve No. 3); per cent of CO in flue gases (curve No. 4); per cent of oxygen (ultimate analysis) in dry coal (curve No. 5); per cent of available hydrogen in "combustible" (curve No. 6); and per cent of fixed carbon (proximate analysis) (curve No. 7). Series of 1905–6; black smoke taken as 100 per cent.

the coals producing little smoke, probably owing to the fact that many lignites were included in these groups, the excess of air reducing the heat available for the boiler and causing a greater loss of heat up the stack. The loss up the stack decreases and the efficiency 72* rises with reduction in the supply of air until the point is reached at which the loss due to incomplete combustion becomes larger than

the gain obtained by reducing the loss up the stack. Curves Nos. 3 and 4 support this explanation.

Curve No. 3 shows that the combustion-chamber temperature rises in direct proportion with the per cent of black smoke. Rise in combustion-chamber temperature always indicates a decrease in air supply.

Curve No. 4 shows a gradual increase in CO in the flue gases. The unaccounted-for loss, represented by curve No. 2, also rises as the smoke increases. It is reasonable to say that the greater part of the increase in the unaccounted-for loss is due to incomplete combustion of hydrocarbon gases and to the escape of solid particles of carbon-forming smoke.

Curve No. 5 shows but a small increase in oxygen in coal, and therefore does not indicate that oxygen in coal is a direct cause of smoke.

Curves Nos. 6 and 7 indicate that, excepting the first point at the extreme left, good or bad coals have not been prevalent in any one group.

The direct cause of the smoke seems to be shown in curve No. 3, which indicates increased rate of combustion and decreased supply of air.

The table which follows indicates that eastern coals are about as apt to smoke as western. It should be stated here that if these coals had been handled as suggested below most of them would probably have burned entirely without smoke, and the remainder with less smoke than they produced as actually handled.

Average per cent of black smoke produced by burning coals from certain localities under a Heine boiler.

Locality.	Number of tests.	Average per cent of black smoke.	Locality.	Number of tests.	Average per cent of black smoke.
Alabama	8	10.2	North Dakota	1	0
Arkansas	6	0	Ohio	25	32.2
Brazil	2	0	Pennsylvania	18	18.3
Florida	1	54.8	Rhode Island	1	0
Illinois	35	18	Tennessee	29	14.6
Indiana	30	26	Texas	3	8.7
Kansas	2	22.7	Utah	3	2.8
Kentucky	4	18.5	Virginia	10	36.1
Maryland	3	5.2	Washington	4	19
Missouri	7	17	West Virginia	23	22.9
New Mexico	8	17.6	Wyoming	8	14.7

The following table includes coals from many localities; some of them are usually called "smoky coals." It is quite probable that most other coals which produced smoke could have been burned smokelessly if the boiler division had not worked for the greater part of 1905 under the idea that very high temperatures are needed to get good over-all efficiencies. As shown elsewhere, extremely high furnace temperatures and a high degree of completeness of combustion in the furnace are incompatible. More air should usually have

been admitted through the smoke-preventer openings to the space over the fire; this precaution might have prevented almost wholly in most cases the formation of the smoke without affecting the over-all efficiency of the outfit.

Coals burned under Heine boiler without producing smoke.

	Test No.
Alabama No. 3	390
Alabama No. 4	378
Arkansas No. 7 A	293, 294
Arkansas No. 8 (washed)	308, 309
Arkansas No. 10	340
Brazil No. 1	172, 173
Illinois No. 6 B (briquets)	313
Illinois No. 11 C (briquets)	312
Illinois No. 20	292
Illinois No. 21	316
Illinois No. 21 (briquets)	318
Illinois No. 23 A (washed)	317
Illinois No. 25	338, 339
Indiana No. 7 B (briquets)	288
Maryland No. 1 (washed)	231
Missouri No. 5	320
New Mexico No. 3 B	389
North Dakota No. 3	206
Pennsylvania No. 8	236, 237
Pennsylvania No. 8 (dried)	242
Rhode Island No. 1	401
Tennessee No. 5	352
Tennessee No. 6	379, 381
Tennessee Nos. 8 A and 8 B (washed)	388
Tennessee No. 9 (washed, briquets)	393
Texas No. 4	291
West Virginia No. 19	285, 289
West Virginia No. 19 (briquets)	331
West Virginia No. 21	297
Wyoming No. 2 B	210
Wyoming No. 3	211

COMBUSTION AND COAL.

"VOLATILE MATTER," "FIXED CARBON," "WATER OF COMPOSITION,"[a] AND "COMBUSTIBLE."

There still lingers a trace of an old idea that coal consists of particles of carbon cemented together with a sort of natural bitumen. The present tendency is to regard bituminous coal as a mixture of dozens, or even hundreds, of organic compounds, most of them derived from cellulose and many of them containing nitrogen and sulphur organically combined. It is true that for most kinds of coal group formulas can be devised which represent very closely the chemical compositions of the respective groups as shown by ultimate analyses; but it must be distinctly borne in mind that the devisers of these formulas do not mean that any one coal under consideration consists of one compound expressed by the formula proposed. Such formulas are meant as collective only; in exactly the same way as physiologists speak of the normal or average man, whose height, weight, etc., bear certain accurate relations to each other, although there is not in the world any one man who fits the description exactly.

When coal is heated, some or most of its constituent compounds are always broken down more or less, but are broken down differently, according to the particulars of the distillation method. That por-

[a] For definition of "water of composition," see the glossary, p. 183.

tion which is distilled off from coal when it is heated under certain "standard" conditions is called "volatile matter." But inasmuch as the "standard" conditions are seldom exactly alike, and inasmuch as "volatile matter" is the product of a change, it is a mistake to say that coal contains any stated percentage of "volatile matter," or even that it contains "volatile matter" at all. The terms "fixed carbon," "volatile carbon," and "water of composition" are equally misleading. Coals do not literally contain these constituents in any more exact sense than cane sugar consists of "water" and "charcoal," although hydrogen and oxygen are contained in cane sugar in exactly such proportions as form water and leave carbon when the sugar is heated.

GRATE AND COMBUSTION SPACE.

Any furnace consists of the grate and the combustion space. The combustion space extends from the top of the fuel bed to the opening into the tube chamber, and its rear portion is termed the "combustion chamber." The function of the grate and fuel bed is to distill the "volatile matter" and partly to burn the "fixed carbon" of the coal. The function of the combustion space is to burn the "volatile matter." With coals high in "fixed carbon" combustion is nearly complete a short distance from the top of the fuel bed; with highly volatile coals the combustion is incomplete, even at the rear of the combustion chamber.

Samples of furnace gas collected at the top of the fuel bed are very commonly rich in combustible ingredients. In the subjoined table is given the chemical composition of gas collected at the top of the fuel bed and also from the combustion chamber, determined from samples collected with the water-jacketed sampler. The samplers projected about 10 inches into the furnace, both being inserted through holes in the side wall, the first sampler resting on the surface of the fuel bed.

Analyses of samples of gas collected at top of fuel bed and rear of combustion chamber.

Collections.	Time.	CO_2.	O_2.	CO.	H_2.	CH_4.	C_nH_{2n+2}.
Test 362:							
Top of fuel bed	8.40	6.1	0	17.9	7.8	3.6	0.2
	10.40	10.8	5.6	2.2	0	0	0
Rear of combustion chamber	8.30	11.4	7.7	0	.....	.....	.....
	10.30	14.4	3.0	0	.....	.....	.....
Test 364:							
Top of fuel bed	8.15	8.4	8.9	2	0	0	0
	12.30	5.7	0	20.3	6	2.7	0
Rear of combustion chamber	8.30	12.6	6	0	.....	.....	.....
	12.30	12.6	5.6	0	.....	.....	.....
Test 367:							
Top of fuel bed	7.30	4.4	7.4	9.5	1.2	2.4	.8
	9.30	5.4	0	23.6	7.8	1.2	.2
	11.20	5.2	.2	23.8	5.4	1.8	0
Rear of combustion chamber	7.30	13.3	0	.9	.....	.....	.....
	9.30	15.5	.6	.7	.....	.....	.....
	11.30	14.6	.2	1	.....	.....	.....

It is difficult to say whether the samples collected with the water-jacketed sampler are really representative samples of the furnace gases. Some constituents of the gas may decompose and reunite in different ways when suddenly cooled by the water-cooled surface. Chemical analyses of gas collected at the end of the combustion chamber seldom show much CO or any H_2 and CH_4.

Samples collected at the base of the stack show dilution of 25 to 30 per cent. The following table gives the chemical analyses of some gas samples collected simultaneously at the base of the stack and from the rear of the combustion chamber:

Analyses of samples of gas collected in test 305.

Place.	Time.	CO_2.	O_2.	CO.	CH_4.	Sum.
Rear of chamber	9.00	13.4	4.6	.....	.....	18
Do	9.30	15.0	3.6	0	0.4	19
Do	10.30	14.4	3.1	0	0	17.5
Do	12.30	15.4	1.8	0	.....	17.2
Do	1.30	14.6	3.2	0	.....	17.8
Average	.....	14.5	3.3	0	.....	17.8
Base of stack	9.00	10.0	9.2	0	.....	19.2
Do	9.30	11.0	7.8	0	.....	18.8
Do	10.30	11.2	7.6	0	.....	18.8
Do	12.30	11.0	7.9	0	.....	18.9
Do	1.30	10.5	7.9	0	.....	18.4
Average	.....	10.7	8.1	0	.....	18.8

The above analyses give 17.5 and 23.2 pounds of gas, respectively, per pound of carbon.

If the flue-gas analyses determine the control of the fire, it is important that the samples analyzed be collected before the gas is diluted. As it is almost impossible to have a perfectly air-tight boiler setting, it is perhaps best to take the sample from the combustion chamber.

VELOCITY OF COMBUSTION AT VARIOUS POINTS ALONG THE FLAME.

The chemical law of mass action for two reacting substances states that, other things being equal, the number of new molecules of resulting compound (in the present case CO_2) formed per second is proportional to the product of the masses of the reacting substances present per unit of volume (of gases in the present case), these masses being expressed in terms of gram molecules. (The gram molecule of a substance is the weight of the substance, in grams, numerically equal to its molecular weight.) There are two atoms in an ordinary molecule of oxygen gas, each weighing sixteen times as much as an atom of hydrogen. Therefore the molecular weight of gaseous oxygen is 32. The molecular weight of CO is $12+16=28$.

Actual volumetric analyses of the simultaneous compositions of gas samples collected from two points along the gas stream of combustion are given on the following page.

Volumetric analyses of samples of gas collected in test 351.

Place.	CO_2.	O_2.	CO.
Top of fuel bed	12.60	1.70	7.10
Rear of combustion chamber	10.90	8.23	.20

The hydrocarbon and hydrogen values are omitted for this problem, although they sometimes amount to several per cent at the surface of the fire; in this calculation the effect of considering them would simply be to intensify the final conclusion. At the top of the fuel bed there was present by volume 1.70 per cent of oxygen and 7.10 per cent of CO. Multiplying each percentage by its specific gravity (so as to get numbers proportional to the masses present), and dividing in each case by the molecular weights above given, we have:

$$1.70 \times 1.105 \div 32 = 0.0588$$
$$7.10 \times 0.967 \div 28 = .245$$

If we assume that the reaction between CO and O_2 is trimolecular, which is probably the case, because two molecules of CO react with one of O_2, then the rapidity with which CO burns is proportional to $CO \times CO \times O_2$, or $CO^2 \times O_2$, and the rapidity of combustion of CO in the two places is, at the top of the fuel bed, $0.245^2 \times 0.0588 = 0.00353$; at the end of the combustion space, $0.00681^2 \times 0.284 = 0.00001337$. 0.00353 is considerably larger than 0.00001337 and therefore the rapidity of combustion is much greater at the top of the fuel bed than at the end of the combustion space (the difference in temperature being neglected).

The curve of chemical activity would drop off rapidly as the gases proceeded along their path in the combustion chamber, so that if the rates of combustion were plotted as ordinates along a base of travel of gases, the resulting curve would look much like the expansion curve of an engine-indicator diagram.

The practical value of such calculations is that they afford a mathematical verification of a fact frequently observed—that mere length of combustion chamber counts for little compared with some device for thoroughly mixing the gases of the flame stream; one good mixing wall or baffle is probably worth many feet of undisturbed flow.

The possibility that many of the molecules of oxygen gas are dissociated at high temperatures into their component atoms does not affect the above calculation, because there would then be more atoms of oxygen looking for molecules of CO, per volume of gases, in just the proportion that the total volume occupied by a given mass of gases would be increased by the dissociation.

COMBUSTION-CHAMBER BAFFLE WALL.

A baffle wall, constructed of special fire brick, was built in the combustion chamber. The object of this wall was to divert the gases from their straight course in order to mix the free oxygen more thoroughly with the unburnt volatile matter of the coal. It was also intended to act as a heat regenerator, absorbing heat when the temperature of the gases was high, and giving it out when the temperature was low, thus keeping the temperature above the ignition temperature of the distilled gases.

It was learned by experiment that only large blocks made of the best material could stand the high temperature and the slagging action

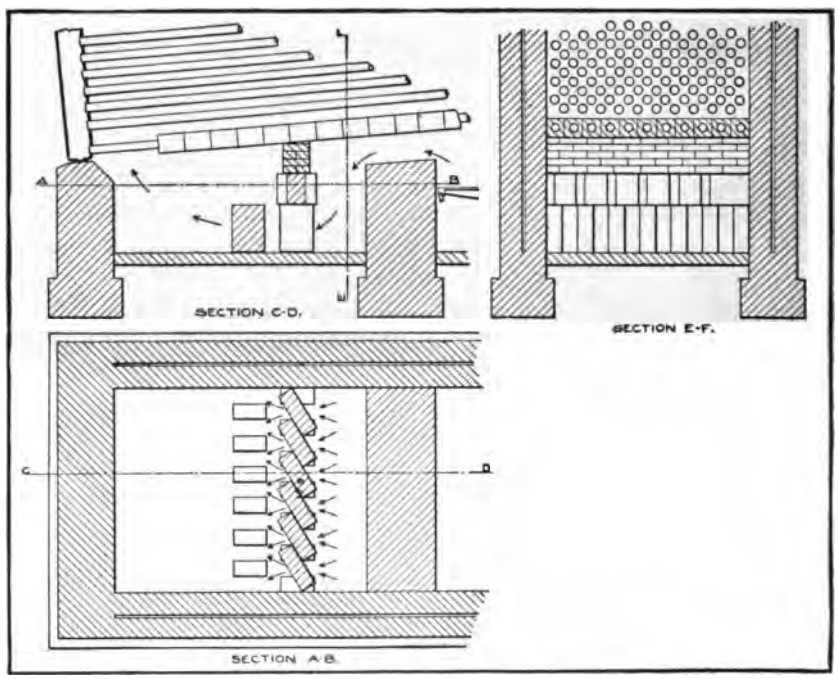

FIG. 34. Gas-mixing wall built in the Heine safety water-tube boiler.

of the gases for any length of time. The baffle wall shown in fig. 34 was built of large fire brick, 18 by 12 by 6 inches, said to be of the best material that could be obtained. The wall was built in three sections. The bottom consisted of seven blocks set on end, forming pillars, on top of which six similar blocks were laid diagonally across. The space between the baffle thus formed and the tile roof was filled with small bricks of good material, so that the spaces between the pillars gave the only passage left for the gases. The object of this construction was to divert the stream of furnace gases, which struck the upper portion of the baffle, and break it into many smaller streams,

thus mixing the distilled gases and the free oxygen. It is probable that eddies caused by the obstacles in the path of the gases greatly aided the mixing. The first baffle wall of this construction lasted just six months, but later ones were not so durable, and such walls were finally abandoned, at least temporarily, and replaced by three small piers set on the bridge wall. The first baffles, however, were far more efficient as smoke preventers and heat regenerators, although they absorbed considerably more draft.

COMBUSTION-CHAMBER TEMPERATURE.

Fig. 35 shows the manner in which the "unaccounted-for" and flue losses of about 260 tests vary to some extent inversely. The encircled

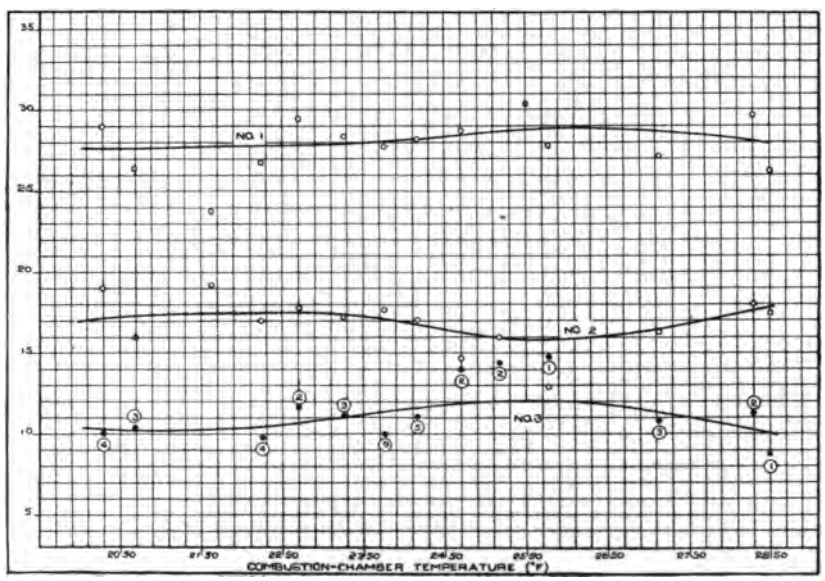

FIG. 35.—Relations of combustion-chamber temperature (°F.) to heat balance (with Illinois and Indiana coals): Curve No. 1, per cent of unaccounted-for loss plus per cent of loss up stack; curve No. 2, per cent of loss up stack; curve No. 3, per cent of unaccounted-for loss.

numbers near the points indicate the number of tests falling within each temperature group. The inverse variation of these curves is a consequence of the facts that the flue-gas analyses, though accurate in themselves, were misleading because of air infiltration, and that the flue temperatures obtained were unreliable because of inherent difficulties; both these causes are discussed in the section devoted to accuracy and reliability of data (pp. 149–151). It is noticeable on this chart that the sum of the flue loss and unaccounted-for loss increases slightly with rise of temperature, notwithstanding the fact that the efficiency of the boiler as a heat absorber increases several per cent with the rise of temperature; thus again the indication is that higher temperatures accompany less complete combustion.

ATTEMPTS TO EXPLAIN UNACCOUNTED-FOR LOSS IN HEAT BALANCE.

The large percentage of "unaccounted-for" loss appearing in the heat balances of the many tests made by the boiler division has long been a cause of discussion.

The settings of the boilers used for testing the various coals have been, even with the utmost diligence, in a very unsatisfactory condition. There were numerous air leaks, so that the furnace gases were always diluted when they reached the base of the stack. It was thought that this dilution of gases introduced error in the calculation of heat loss up the stack. It also seemed that the radiation loss was larger than it should be.

Recently a new setting has been built and completely inclosed by a sheet-iron casing made with air-tight joints, so that the leakage was reduced to a minimum. The walls of the new setting were built of hollow tiles and this with the addition of a sheet-metal casing should have reduced the radiation loss; at least this loss could not be greater than formerly. Still the unaccounted-for loss continues.

A great many classifications have been made on the data and results obtained from our tests. In all cases a few relations continually appear. The important one in this discussion is that low efficiency is always accompanied by the highest per cent of CO in the flue-gas analysis, and the highest efficiency by the lowest per cent of CO. Moreover, the high CO values always go with the highest combustion-chamber temperatures. It is also found that as the combustion-chamber temperature increases the per cent of black smoke increases.

It is not possible to account for very much of the loss in burning coal by the amount of CO found in the gas analysis. Therefore it seems that this appearance of CO in the gas analysis is indicative of bad conditions, such as an irregular fuel bed or the escape of hydrocarbons unburned.

RELATION OF NITROGEN IN FLUE GASES TO EFFICIENCY 72* AND TO SIZE OF COAL, AND OF PER CENT OF CO TO EFFICIENCY 72*.

The curves of fig. 19 (p. 28), based on tests 89 to 401, inclusive, present a combination of two charts. The upper one classifies the tests on a nitrogen basis. This nitrogen is presumably what is left in the flue gases after subtracting from 100 the sum of the percentages by volume of carbon dioxide, oxygen, and carbon monoxide, neglecting any small traces of hydrocarbons which may have been present and were not determined. Curve No. 1 indicates that the code "boiler efficiency" (72*) increases markedly when the nitrogen content rises from 80 to 81 per cent—that is, when Orsat gas-analysis totals decrease from 20 to 19 per cent. The reader can

choose between the many possible conjectures as to the fundamental significance of this curve.

Curve No. 2 indicates that for any size of coal, up to maximum size, two different gas analyses may be obtained. The reader may make whatever conjectures he chooses.

Curve No. 3, in the lower chart, is very significant. It indicates that a volumetric percentage of CO above 0.4 per cent is threatening to efficiency. Inasmuch as these were analyses of flue gases, into which 10 to 50 per cent of air had filtered after the gases of combustion passed through the combustion chamber (p. 64), this CO content represents a much larger value. The significant fact is that an increase of CO content from 0.3 to 1 per cent is of itself sufficient to account for only about one-third of the drop from 65 to 54 per cent in code "boiler efficiency" (72*). Figs. 13 (p. 22) and 14 (p. 23) show that the percentage of CO rises with the temperature of combustion; further, the efficiency of the boiler as a heat absorber increases slightly with a rise of furnace temperature; we therefore reach the inevitable conclusion that at least two-thirds of the large drop in code "boiler efficiency" (72*) with rise of CO is due to incomplete combustion losses not represented by CO, so that high CO is a decided danger signal. Curve No. 1 of fig. 18 (p. 27) shows exactly the same thing, with grouping on a "boiler efficiency" (72*) basis. With CO rising from 0.3 to 0.6 per cent the "efficiency" drops from 60 to 55 per cent. The same range of CO in fig. 19 (p. 28) gives the same amount (65 to 60 per cent) of efficiency drop—though in a different region—which is explained by the fact that in grouping any set of related occurrences in different ways the same tests will not often fall in successive groups. For instance, only part of the tests falling in the middle group in one classification are apt to fall in the middle group in any other classification.

RELATION OF CO_2 IN FLUE GASES TO PER CENT OF COMPLETENESS OF COMBUSTION (E_3).

The curve of fig. 31 (p. 51) was obtained by grouping tests according to volumetric CO_2 content of flue gases and then averaging the per cent of completeness of combustion (E_3) of each group. These values of E_3 were obtained by the mathematical calculation explained on page 139, and although many or all of them may be considerably in error, it is likely that the general shape and the amount of drop of this curve are nearly correct.

The curve shows clearly that as the oxygen is decreased simultaneously with a rise of CO_2 content the completeness of combustion decreases, which is just what we should expect when reducing the proportion of oxygen molecules present, according to the law of mass action discussed on pages 170–172.

Thus even in furnaces as long as those of the boilers used in the work of the boiler division the increasing incompleteness of combustion with rising temperature is practically sufficient to offset an increase of a few per cent in the efficiency of the boiler as a heat absorber after the furnace temperature has reached about 2,400° F.

RELATION OF DIFFERENCES OF DRAFT TO POUNDS OF DRY CHIMNEY GASES PER POUND OF "COMBUSTIBLE."

The curves of fig. 36 were determined by plotting differences between draft in stack and draft over fire with pounds of dry chimney gases per pound of "combustible." Curve No. 1 represents

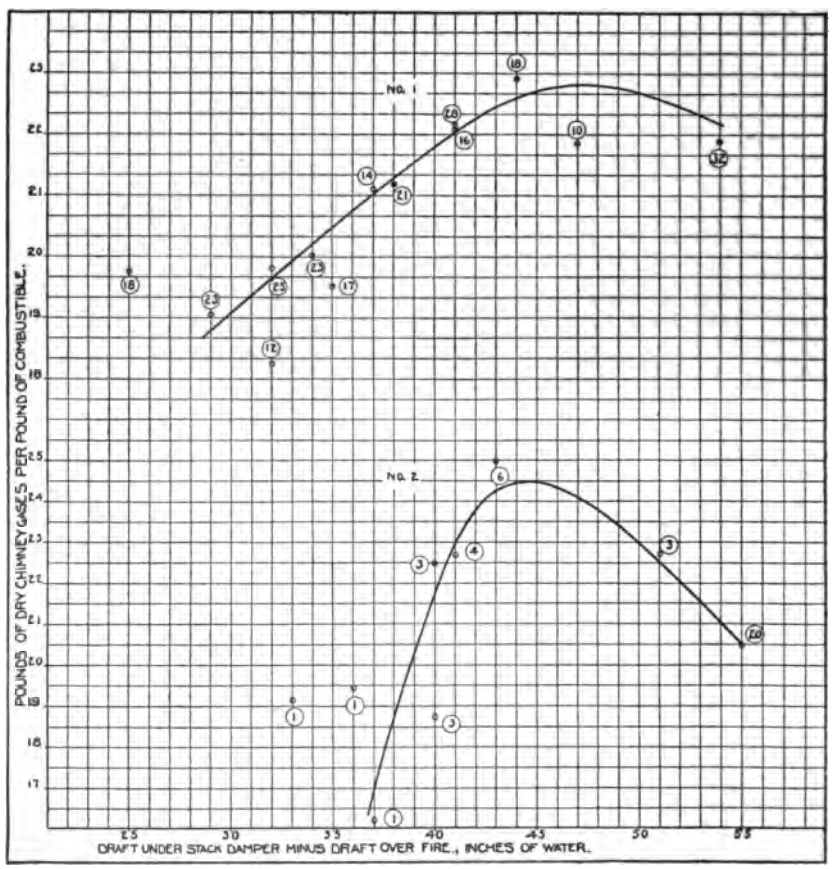

FIG. 36.—Relation of differences between draft in stack and draft over fire to pounds of dry chimney gases per pound of "combustible:" Curve No. 1, figured from analysis of gas in stack, tests 120–400; curve No. 2, figured from analysis of gas in rear of combustion chamber, tests 318–380.

about 200 tests. The values for pounds of dry chimney gases per pound of "combustible" were figured from stack samples. Curve No. 2 is the average of only a few points. The values for pounds of dry

chimney gases per pound of "combustible" were figured from samples taken in the combustion chamber. The general direction of the curve was determined by curve No. 1.

Low difference of draft readings occurs in two ways—by carrying a low-stack draft accompanied by a thin fire or by carrying a high-stack draft and a thick fire. On most of these tests the stack draft is comparatively high as regards the amount of draft obtainable, hence the average points on the low difference of draft may be assumed to result from thick fires.

The use of a thick fire causes resistance to the passage of air through the fuel bed. When high-stack draft is used the difference between the pressure of the gases on the inside of the boiler setting and the atmospheric pressure outside is large, and thereby the absolute amount of leakage of air into the setting is increased. However, since, in general, high-stack draft has been carried, it follows that on the chart the per cent of leakage is a maximum at the points of low-draft differences. That is to say, as the draft difference increases the pounds of dry chimney gases per pound of combustible increase, the per cent of air leakage decreases, and more of the air comes through the fuel bed. This condition holds up to a point where the fire is thin, as indicated by a high-draft difference. The air now enters more freely through the fuel bed, increasing the rate of combustion, thereby decreasing the pounds of dry chimney gases per pound of "combustible." Another cause for the decrease of the pounds of dry chimney gases at the high-draft difference points is the very low per cent of air leakage. Thus it is shown that with two widely varying conditions we may obtain the same weight of dry chimney gases per pound of "combustible."

The curves have no bearing on efficiency. The variation in the slope of curves Nos. 1 and 2 is probably due to air leakage.

The following table gives figures on pounds of dry gases per pound of carbon, calculated from gas analyses taken simultaneously at different parts of the boiler:

Infiltration of air through setting.

Test No.	Pounds of gas per pound of carbon.				Per cent of leakage, combustion chamber to stack.	Test No.	Pounds of gas per pound of carbon.				Per cent of leakage, combustion chamber to stack.
	Over fire.	Combustion chamber.	Front water leg.	Stack.			Over fire.	Combustion chamber.	Front water leg.	Stack.	
318	.....	18.38	19.20	23.34	27.0	355	15.29	20.90	25.42	26.78	28.0
319	.....	24.02	27.89	32.42	34.9	356	18.22	19.84	22.50	25.28	27.3
320	.....	23.76	25.31	28.37	21.5	357	13.65	20.68	18.38	29.12	40.8
321	.....	16.85	19.64	23.20	37.7	359	.....	21.88	.....	26.78	22.4
323	.....	16.17	17.88	21.60	33.6	360	.....	20.50	.....	25.16	22.7
324	.....	19.93	23.75	26.51	33.0	361	.....	19.04	.....	25.49	33.8
325	.....	19.44	22.40	27.30	40.4	362	13.27	22.48	19.89	29.70	32.2
326	.....	20.38	23.83	31.45	54.3	363	.....	21.81	.....	27.17	24.4
327	.....	23.21	25.50	28.87	24.3	364	12.45	19.15	18.14	25.30	32.1
328	.....	17.96	21.[illegible]	24.42	35.9	365	.....	21.10	.....	29.18	38.3
329	.....	.....	23.38	26.90	.....	366	.....	22.29	.....	26.02	16.8
330	.....	.....	21.51	25.09	.....	367	11.77	18.44	16.85	26.40	43.2
332	.....	.....	18.62	23.60	.....	369	.....	21.89	.....	27.73	26.7
334	.....	.....	21.09	24.26	.....	370	.....	22.22	.....	27.78	24.9
344	.....	21.70	.....	27.85	27.7	371	.....	30.90	.....	37.05	19.9
347	10.22	19.40	.....	26.80	38.1	372	.....	19.14	.....	24.54	28.2
348	12.12	17.53	.....	24.52	39.9	375	.....	20.02	.....	26.48	32.1
349	7.77	14.76	.....	20.86	41.3	376	.....	22.48	.....	30.05	33.7
349	11.15	15.78	.....	.....	.....	377	.....	26.26	.....	34.48	31.3
350	10.54	16.31	.....	23.41	43.5	378	.....	30.48	.....	32.05	5.1
351	12.73	22.91	24.25	20.25	32.0	379	.....	25.02	.....	27.72	10.8
352	.....	20.51	26.87	27.21	32.6	380	.....	25.80	.....	30.70	19.0
353	15.17	22.15	20.61	25.57	15.3	381	.....	28.21	.....	32.20	14.2
354	.....	25.27	27.83	32.00	26.6						

Average per cent increase from surface of fire to combustion chamber, 52.33; from combustion chamber to front leg, 8.43; from front leg to stack, 21.25; from combustion chamber to stack, 28.48.

CLASSIFICATION OF COALS.

CARBON-HYDROGEN RATIO IN AIR-DRIED COAL.

In the belief that coals of approximately the same proportions of constituents, as shown by chemical analysis, should behave more nearly alike when subjected to similar treatment than coals in which the proportions of the constituents vary widely, the following attempts have been made to classify the coals burned by the boiler division, according to their performance under a boiler.

In accordance with the method proposed by Marius R. Campbell,[a] the ratios of carbon to hydrogen in the ultimate analyses of air-dried car samples were computed. One hundred and seventy-four tests on about 75 different coals were employed for this purpose, washed, dried, and briquetted coals being rejected. It was not expected that this classification (fig. 37) would be of as much service as one based on the same ratio of either coal as received or dry coal, since the amount of drying to which a sample is subjected is dependent on the local conditions, which vary from day to day. The statement just made seems to be borne out by the fact that the average

[a] Prof. Paper U. S. Geol. Survey No. 48, 1906, pp. 156-173.

points from which the general efficiency curve (No. 1) is derived fall farther from such a curve than is the case with general curves derived from the ratio of carbon to hydrogen, based on either coal as received or dry coal.

The ratio of carbon to hydrogen should have been obtained from the ultimate analysis of the boiler-test sample after air drying, but these data were not available. The ratio used is calculated on the

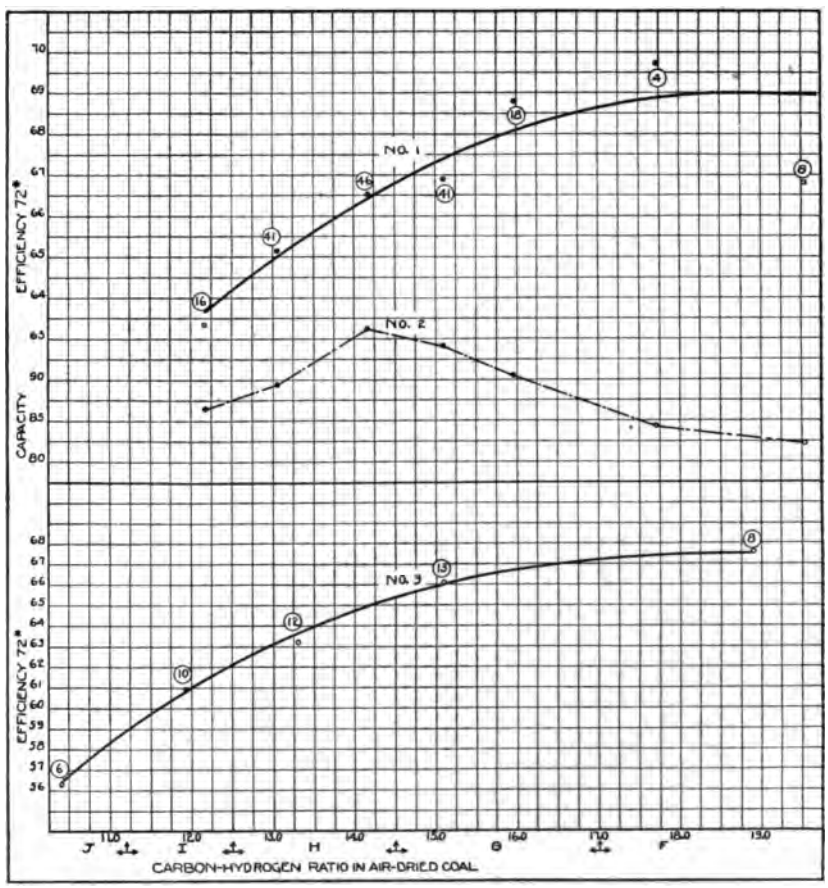

FIG. 37.—Coal classification based on carbon-hydrogen ratio from ultimate analysis of air-dried car samples as related to efficiency 72*, tests 120-401 (curve No. 1); per cent of rated capacity developed (curve No. 2); and efficiency 72* at about rated capacity, tests 1-78 (curve No. 3). General curves, omitting tests of washed, dried, and briquetted coals.

air-dried coal of the car sample—a fact which might account for some of the variations of some of the points from the curve.

The broken line, curve No. 2, is drawn through the average per cent ratings for all tests coming in each group. The per cent rating attained does not seem to influence the efficiency, as it does in other classifications which follow.

Curve No. 3 shows the relations between carbon-hydrogen ratios on air-dried coal and efficiency from boiler tests conducted during 1904. The tests in which washed and briquetted coals were burned are omitted. It was decided to abandon this classification and to use the ratio of carbon to hydrogen of coal, as received, and of dry coal. The curves and conclusions on classifications based on carbon-hydrogen ratios of coal, as received, and of dry coal, were derived from approximately 250 boiler tests run in one series. The tests included raw, washed, briquetted, and a few mixed coals. The relative values of the classifications were based on the uniformity of the general efficiency curves, efficiency here meaning the efficiency of the boiler on the combustible basis (the combustible consumed, as shown by proximate analysis, less the combustible lost through the grate, as determined by an analysis of the refuse). The item used for the efficiency is 72* of the A. S. M. E. code.

CARBON-HYDROGEN RATIO IN COAL AS RECEIVED.

The carbon-hydrogen ratios of fig. 38 were computed from the ultimate analyses made by the chemical division on boiler-test samples. These ratios were divided into six groups, as follows: Group K, including all values up to 11.2; group L, from 11.2 to 12.5; group M, from 12.5 to 14.5; group N, from 14.5 to 15.5; group O, from 15.5 to 17.0, and group P, all values over 17.0. The several items in each group were then averaged and curves plotted on the basis of (1) efficiency 72*; (2) per cent of CO loss; (3) combustion-chamber temperature (by Wanner optical pyrometer); (4) per cent of rated capacity of boiler; (5) pounds of dry chimney gases per pound of "combustible" (coal free from ash and moisture), and (6) B. t. u. per pound of dry coal.

A comparison of the averages just mentioned shows that no one item was maintained, even approximately, constant, so that whatever conclusions may be drawn therefrom must necessarily be considered anything but absolute. Particular mention should be made of the per cent of rated capacity attained in the trials, which, if maintained constant, might have aided materially in defining more closely the relative causes and effects as indicated by the other items, although it is believed that these items are as much dependent on the kind of coal as on the per cent of rated capacity attained.

The averages of all of the like items of each group are graphically represented on the accompanying charts (figs. 39–45), on which the ratio of carbon to hydrogen appears as an abscissa.

The curves of efficiency 72* in figs. 38 and 39 do not agree; but it is hardly to be expected that items should vary alike when tests are classified on such an illogical basis as the carbon-hydrogen ratio in coal as fired, inasmuch as the hydrogen of the free moisture is also included.

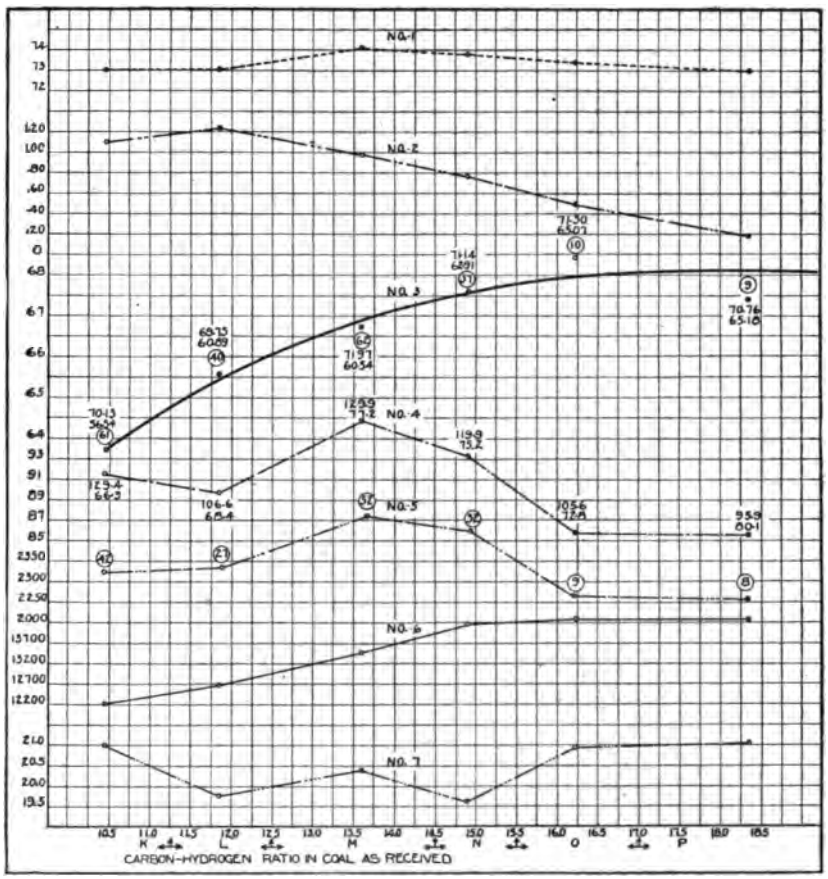

FIG. 38.—Coal classification based on carbon-hydrogen ratio as related to theoretical relative efficiency of boiler as a heat absorber at various temperatures (curve No. 1); per cent of CO loss (curve No. 2); efficiency 72* (curve No. 3); per cent of rated capacity developed (curve No. 4); combustion-chamber temperature (°F.) (curve No. 5); B. t. u. per pound of dry coal (curve No. 6); and pounds of dry chimney gases per pound of "combustible" (curve No. 7). General curves, samples as received, tests 120-380.

The following list gives the coals appearing in each group and their respective carbon-hydrogen ratios:

Average carbon-hydrogen ratios determined from analysis of boiler-test samples of coal as fired, including moisture.

Group P (all values over 17.0):

Arkansas No. 8	20.32
Maryland No. 1	19.13
Maryland No. 1 (washed)	18.28
Pennsylvania No. 8	18.02
West Virginia No. 19	17.16

Group O (from 15.5 to 17.0):

West Virginia No. 19	16.93
Arkansas No. 7 A	16.79
West Virginia No. 17	16.27
West Virginia No. 17 (washed)	16.15

Group O (from 15.5 to 17.0)—Continued.

Virginia No. 3	16.02
Pennsylvania No. 7	15.65
West Virginia No. 18	15.63

Group N (from 14.5 to 15.5):

Virginia No. 3	15.46
West Virginia No. 14	15.45
Pennsylvania No. 4	15.27
Pennsylvania No. 7 (washed)	15.10
Ohio No. 5	15.15
Pennsylvania No. 6	15.10

Group N (from 14.5 to 15.5)—Continued.

West Virginia No. 13	15.04
West Virginia No. 20	14.97
Virginia No. 4	14.86
West Virginia No. 15	14.84
Virginia No. 2	14.83
Tennessee No. 6	14.78
Kentucky No. 5	14.77
Pennsylvania No. 10	14.74
Pennsylvania No. 7	14.72
West Virginia No. 20 (washed)	14.72
Tennessee No. 9	14.70
Pennsylvania No. 5 (washed)	14.66
West Virginia No. 21	14.57

Group M (from 12.5 to 14.5):

West Virginia No. 21	14.43
Tennessee No. 9	14.40
West Virginia No. 21 (washed)	14.36
Pennsylvania No. 5	14.25
Kentucky No. 1 C	14.17
Kentucky No. 6	14.16
Virginia No. 1 B	14.14
Ohio No. 9 A	14.11
Ohio No. 9 B (washed and dried)	13.98
Ohio No. 5	13.89
Ohio No. 4	13.89
Ohio No. 4 (washed)	13.76
Tennessee No. 7 A	13.73
Ohio No. 6 (washed)	13.73
Tennessee No. 2	13.70
Alabama No. 4	13.63
Tennessee No. 1	13.62
Ohio No. 6	13.55
Washington No. 2	13.38
Tennessee No. 5	13.24
Tennessee No. 4	13.04
Tennessee No. 3	13.01
Illinois No. 11 A	12.92
Ohio No. 7	12.76
Illinois No. 16	12.73
Illinois No. 19 B	12.73
Ohio No. 9 B (washed)	12.52

Group L (from 11.2 to 12.5):

Kansas No. 6	12.41
Ohio No. 3 (washed)	12.33
Ohio No. 9 B	12.31
Illinois No. 13 (washed)	12.27
Kentucky No. 7	12.22
Illinois No. 13	12.22
Illinois No. 19 A	12.11
Indiana No. 11	12.00
Illinois No. 12	11.95
Ohio No. 8	11.91

Group L (from 11.2 to 12.5)—Continued.

Illinois No. 12 (washed)	11.85
Ohio No. 2 (washed)	11.77
Indiana No. 7 A	11.71
Ohio No. 2	11.62
Kansas No. 6 (washed)	11.61
Indiana No. 8	11.49
Ohio No. 1	11.47
Indiana No. 7 B	11.43
Indiana No. 7 B (briquetted)	11.38
Ohio No. 1 (washed)	11.38
Illinois No. 22 A	11.35
Indiana No. 5	11.32
Illinois No. 15	11.25
Indiana No. 6	11.21

Group K (all values up to 11.2):

Indiana No. 6 (washed)	11.18
Indiana No. 8 (washed)	11.13
Indiana No. 5	11.12
Illinois No. 15 (washed)	11.07
Illinois No. 22 A	10.98
Illinois No. 9 B	10.95
Illinois No. 24 B	10.92
Illinois No. 7 D	10.91
Indiana No. 12 (washed)	10.87
Indiana No. 10 (washed)	10.86
Indiana No. 9 A	10.84
Illinois No. 14	10.83
Indiana No. 9 B	10.80
Indiana No. 10	10.79
Wyoming No. 2 B	10.79
Indiana No. 4 (washed)	10.75
Illinois No. 18	10.70
Indiana No. 12	10.68
Missouri No. 6	10.67
Illinois No. 22 A (washed)	10.65
Indiana No. 4	10.52
Illinois No. 25	10.51
Missouri No. 5	10.47
Illinois No. 21	10.46
Illinois No. 26	10.43
Indiana No. 3	10.38
Illinois No. 20	10.15
Illinois No. 23 A (washed)	10.10
Illinois No. 14 (washed)	10.09
Illinois No. 18 (washed)	10.03
Illinois No. 20 (washed)	9.96
Mixed coal	9.95
Illinois No. 23 A	9.90
Illinois No. 7 C (washed)	9.82
Illinois No. 27	9.71
Missouri No. 7 (washed)	9.67
Washington No. 1 B	9.61
Wyoming No. 3	9.44
Wyoming No. 3 (washed)	8.94

The curve drawn along the average-efficiency points on the chart is so uniform that the conclusion might easily be reached that a classification such as the ratio of carbon to hydrogen is of great value. If an individual group is selected there is no such close agreement, as is shown by the range of efficiencies noted at each point of the general-efficiency curve. The curve shows a gradual increase of efficiency as the ratio of carbon to hydrogen increases, becoming horizontal for the high ratios.

A comparison of the highest efficiencies of the groups shows a marked uniformity. The range of efficiencies in each group (not shown on the chart) decreases as the ratio of carbon to hydrogen increases, seeming to indicate that efficient burning of coals of a lower carbon-hydrogen ratio is a matter of much greater uncertainty than when the ratio is high.

The curve of per cent of CO loss indicates maximum incomplete combustion in the low-ratio groups, decreasing to nearly zero in the high-ratio groups. This is in accord with the statement made regarding the uncertainty of burning coals of a low carbon-hydrogen ratio.

The B. t. u. curve, No. 6, rises as the carbon-hydrogen ratio increases.

A broken line connecting the averages of the per cent of rated capacity of each group is shown, curve No. 4. This line points out a wide variation in capacity attained. The figures given with each point on the general curve show a much wider range of the same item as between the different trials of each group than between groups. The variation of per cent of rating tended to remove the average efficiency from a uniform efficiency curve; the average efficiency increased, in general, as the average per cent of rating decreased.

From the points showing combustion-chamber temperature we obtain a broken line which is very nearly parallel to the line of per cent of rated capacity, as on many other charts. The highest temperatures were obtained in the middle groups, the lowest temperatures in the highest groups.

The line representing the number of pounds of dry chimney gases per pound of combustible (curve No. 7) can best be studied on the charts of the separate groups; on the general chart it is difficult to arrive at conclusions so far as this one item is concerned.

Curve No. 1 in the chart is merely tentative and is put on to show relatively the theoretical efficiency of the boiler as an absorber of heat generated, the calculation being based on the theory, developed on pages 107–108, that the heat absorption is a function varying slightly with combustion-chamber temperature; for this purpose the temperatures used are those on the line of combustion-chamber temperatures. It will be noticed that the line of theoretical boiler efficiencies varies less than 2 per cent; it may be too high or too low at every point by 2 per cent, but it does show that in the lower groups the distance is

greater between this line and that of efficiency 72*. This fact seems to indicate that in the lower groups there was more incomplete combustion—an indication which is verified by curve No. 2, giving per cent of CO loss. It is noteworthy that the best actual efficiencies 72* in all groups were about the same (a fact which is not shown on the chart), indicating that when enough is known about combustion and when special grates, stokers, furnaces, etc., are applied, it will

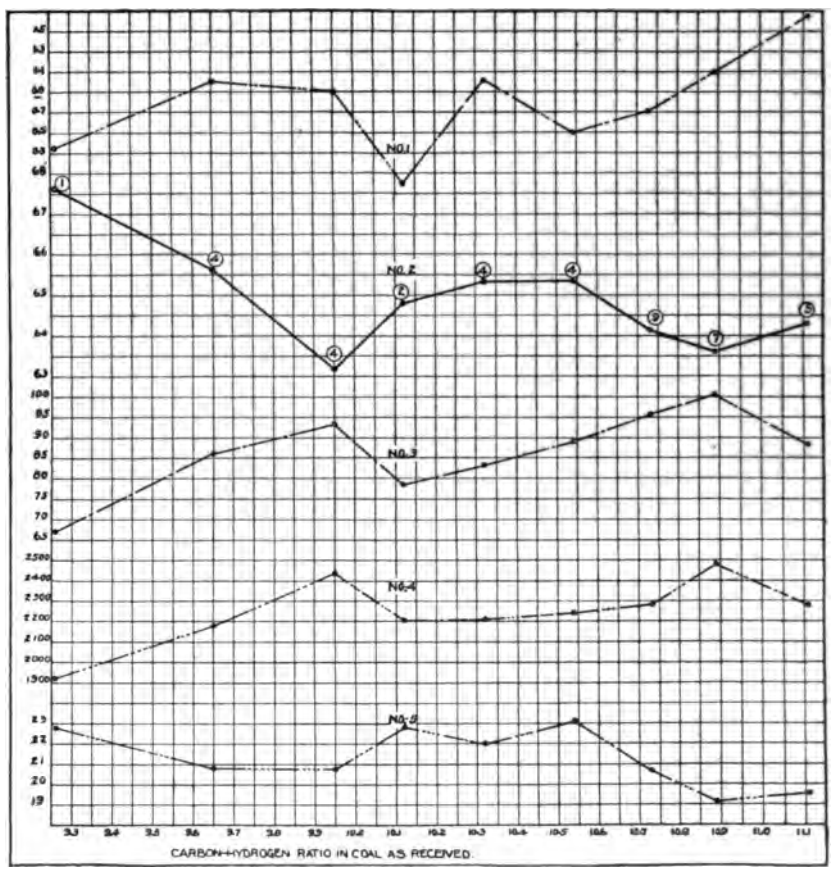

FIG. 39.—Coal classification based on carbon-hydrogen ratio as related to per cent of CO loss (curve No. 1); efficiency 72* (curve No. 2); per cent of rated capacity developed (curve No. 3); combustion-chamber temperature (°F) (curve No. 4); and pounds of dry chimney gases per pound of "combustible" (curve No. 5). Group K, all values up to 11.2, samples as fired.

be possible to burn very poor coals with nearly the same efficiencies as good ones.

In order to discover the variations within the individual groups three charts have been plotted involving the same items as shown on the general chart.

Since the general curve shows a gradual increase in efficiency with an increase of the ratio of carbon to hydrogen, one would naturally

look for a similar increase in efficiency within individual groups. This is not true, however, because of wide variations in the other items within each group.

The efficiency line (fig. 39) in group K varies inversely with the per cent of rating and to a much more marked degree than in the general chart. Also the efficiency falls as the combustion-chamber temperature rises, and vice versa. The line for combustion-chamber temperature is parallel to the line for per cent of rating, as in many other places.

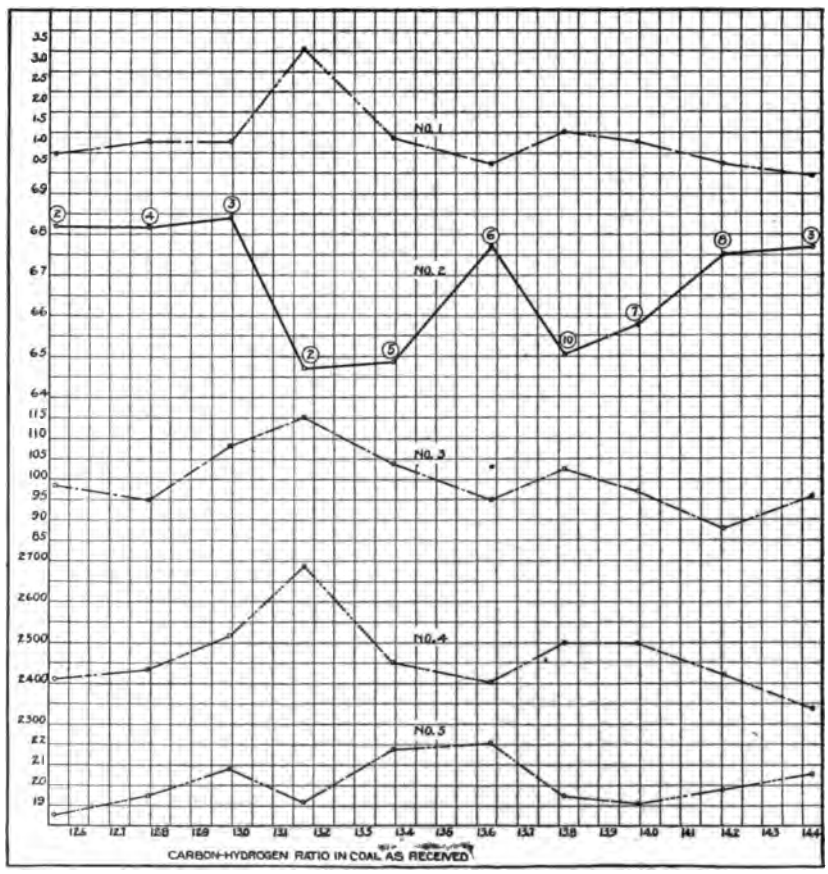

FIG. 40.—Coal classification based on carbon-hydrogen ratio as related to per cent of CO loss (curve No. 1); efficiency 72* (curve No. 2); per cent of rated capacity developed (curve No. 3); combustion-chamber temperature (°F) (curve No. 4); and pounds of dry chimney gases per pound of "combustible" (curve No. 5). Group M, values from 12.5 to 14.5, samples as fired.

The line for per cent of CO loss varies inversely with the line for pounds of dry chimney gases per pound of "combustible," as would be expected from the chemical law of mass action; and in turn the line denoting pounds of air per pound of "combustible" runs parallel in most places with the efficiency line.

Fig. 40 shows that for group M the lines representing the per cent of rating, *combustion*-chamber temperature, and per cent of CO loss

run parallel to one another and vary inversely with the line giving pounds of dry chimney gases per pound of combustible and also in a general way, inversely with the efficiency line; all of which interrelations are much the same as in group K (fig. 39). Relations between variables are brought out very clearly in fig. 40. The general chart shows that group M was the one in which the highest combustion-

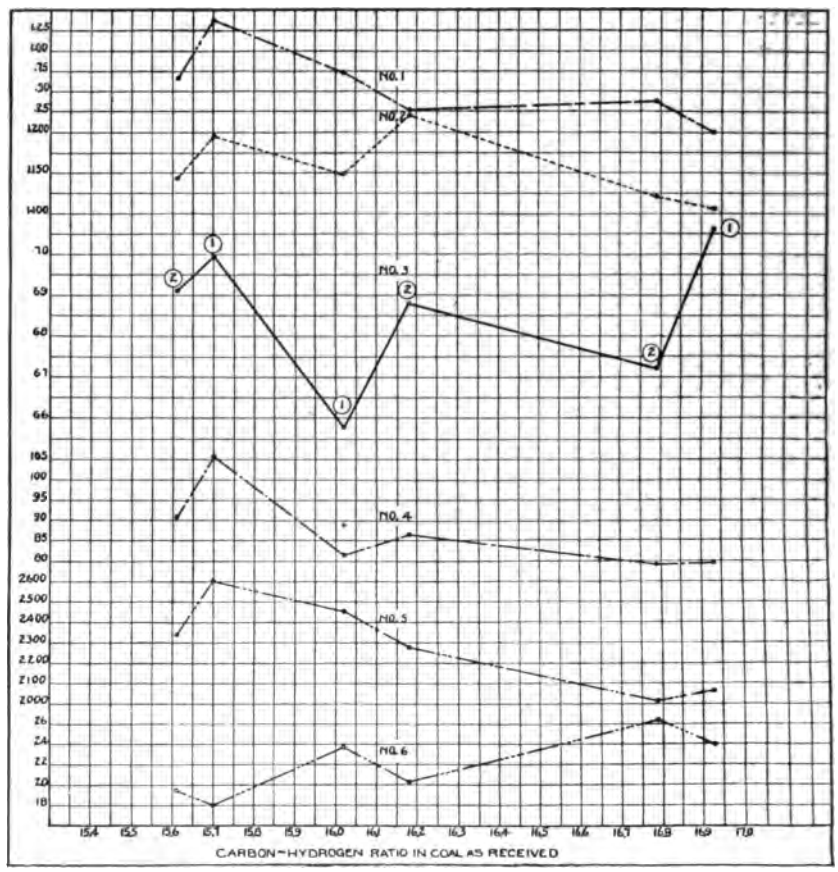

FIG. 41.—Coal classification based on carbon-hydrogen ratio as related to per cent of CO loss (curve No. 1); ratio of hydrogen to available hydrogen (curve No. 2); efficiency 72* (curve No. 3); per cent of rated capacity developed (curve No. 4); combustion-chamber temperature (°F) (curve No. 5); and pounds of dry chimney gases per pound of "combustible" (curve No. 6). Group O, values from 15.5 to 17.0, samples as fired.

chamber temperatures and the highest per cent of rating were obtained.

In group O (fig. 41) the lines of combustion-chamber temperature and per cent of rating are shown parallel with the efficiency line. The per cent of CO loss is small at all times in this group, so little effect could be expected from this cause. The additional curve showing the ratio of hydrogen to available hydrogen is parallel to

the efficiency line. The line for pounds of dry chimney gases, instead of being parallel with the efficiency line, as in other groups, varies inversely with that line, a variation that is concordant with the fact that the small CO loss indicates very little incomplete combustion.

CARBON-HYDROGEN RATIO IN DRY COAL.

Another classification has been made (fig. 25, p. 37) by using the ratio of carbon to total hydrogen, as determined by the ultimate analysis of dry coal. By this method that portion of the hydrogen which appears in the moisture determined by the proximate analyses is eliminated, and consequently there should result a more nearly constant carbon-hydrogen ratio for any given coal. The ratios were divided into seven groups, as follows: Group A, including all values up to 14.5; group B, from 14.5 to 15.0; group C, from 15.0 to 15.5; group D, from 15.5 to 16.0; group E, from 16.0 to 16.5; group X, from 16.5 to 17.5; group Y, all values of 17.5 and over.

As in the previous classification (p. 70) all the values in each group were averaged and each average was plotted with its corresponding average of carbon-hydrogen ratio. The following list shows the coals in each group and their corresponding carbon-hydrogen ratios:

Average carbon-hydrogen ratios determined from ultimate analysis of dry coal.

Group Y (all values of 17.5 and over):	
Arkansas No. 8	22.60
Maryland No. 1	20.16
Maryland No. 1 (washed)	20.14
Arkansas No. 7 A	19.50
Pennsylvania No. 8	19.37
West Virginia No. 19	18.23
West Virginia No. 17	17.92
West Virginia No. 17 (washed)	17.91
Group X (from 16.5 to 17.5):	
Pennsylvania No. 7	17.04
Pennsylvania No. 7 (washed)	17.03
West Virginia No. 18	16.71
Illinois No. 19 A	16.67
Virginia No. 3	16.64
Kentucky No. 5	16.56
Group E (from 16 to 16.5):	
West Virginia No. 14	16.45
West Virginia No. 13	16.44
Ohio No. 9 A	16.38
Illinois No. 19 B	16.21
Virginia No. 4	16.13
Pennsylvania No. 4	16.11
Pennsylvania No. 6	16.07
Tennessee No. 9	16.01
Group D (from 15.5 to 16.0):	
Virginia No. 2	15.96
Tennessee No. 6	15.90
Group D (from 15.5 to 16.0)—Continued.	
Illinois No. 16	15.85
West Virginia No. 20	15.85
West Virginia No. 20 (washed)	15.81
Indiana No. 11	15.78
Virginia No. 1 B	15.73
Kentucky No. 6	15.72
West Virginia No. 21	15.71
West Virginia No. 21 (washed)	15.71
Pennsylvania No. 10	15.65
Pennsylvania No. 5	15.64
Pennsylvania No. 5 (washed)	15.63
West Virginia No. 15	15.58
Illinois No. 11 A	15.57
Kentucky No. 1 C	15.54
Group C (from 15 to 15.5):	
Illinois No. 13	15.46
Illinois No. 13 (washed)	15.43
Ohio No. 5	15.37
Alabama No. 4	15.29
Kentucky No. 7	15.29
Tennessee No. 2	15.26
Kansas No. 6	15.21
Kansas No. 6 (washed)	15.20
Tennessee No. 5	15.17
Ohio No. 3 (washed)	15.09
Ohio No. 4	15.08
Ohio No. 4 (washed)	15.07

Group C (from 15 to 15.5)—Continued.

Tennessee No. 1	15.04
Illinois No. 21	15.03
Indiana No. 4	15.01
Indiana No. 4 (washed)	15.01
Illinois No. 12	15.00

Group B (from 14.5 to 15.0):

Indiana No. 4	14.99
Illinois No. 12	14.97
Illinois No. 12 (washed)	14.94
Tennessee No. 4	14.94
Ohio No. 9 B (washed)	14.94
Ohio No. 9 B	14.93
Mixed coal	14.92
Illinois No. 26	14.86
Illinois No. 22 A	14.77
Tennessee No. 3	14.77
Tennessee No. 7 A	14.77
Illinois No. 22 A (washed)	14.76
Ohio No. 7	14.76
Ohio No. 6	14.74
Ohio No. 6 (washed)	14.71
Missouri No. 6	14.70
Illinois No. 20	14.63
Illinois No. 20 (washed)	14.61
Indiana No. 5	14.59
Illinois No. 24 B	14.56
Missouri No. 7 (washed)	14.51

Group A (all values up to 14.5):

Ohio No. 9 B (washed and dried)	14.48
Indiana No. 8 (washed)	14.48
Indiana No. 8	14.46
Indiana No. 12	14.46
Indiana No. 12 (washed)	14.45

Group A (all values up to 14.5)—Cont'd.

Illinois No. 14	14.45
Washington No. 2	14.45
Mixed coal	14.43
Indiana No. 9 A	14.42
Ohio No. 8	14.42
Illinois No. 14 (washed)	14.42
Illinois No. 15 (washed)	14.40
Indiana No. 7 B (briq.)	14.40
Illinois No. 15	14.39
Indiana No. 7 B	14.36
Missouri No. 5	14.34
Ohio No. 2	14.32
Ohio No. 2 (washed)	14.30
Illinois No. 27	14.30
Indiana No. 6	14.30
Indiana No. 6 (washed)	14.29
Indiana No. 7 A	14.18
Illinois No. 7 C (washed)	14.14
Illinois No. 7 D	14.11
Indiana No. 3	14.01
Illinois No. 9 B	13.96
Indiana No. 9 B	13.95
Illinois No. 23 A (washed)	13.93
Illinois No. 23 A	13.92
Washington No. 1 B	13.85
Illinois No. 25	13.81
Ohio No. 1 (washed)	13.75
Ohio No. 1	13.73
Illinois No. 18 (washed)	13.71
Wyoming No. 2 B	13.71
Wyoming No. 3	13.69
Wyoming No. 3 (washed)	13.68
Illinois No. 18	13.67
Indiana No. 10 (washed)	13.61
Indiana No. 10	13.58

There is no particular difference in the general curves as derived from the two classifications based on dry coal and coal as received. To the general chart (p. 37) two more curves have been added—one for average diameter of coal (No. 7), and one for per cent of clinker in refuse (No. 8). The curve of average diameter of coal as fired shows that as the ratios of carbon to hydrogen increase there is a gradual reduction in average diameter. Nearly all the coals used in the tests passed through the same crusher. It is not to be assumed that the ratio of carbon to hydrogen influences the ease with which the coal breaks, for this can be accounted for in other ways. The coals of low carbon-hydrogen ratio give the highest per cent of clinker in refuse.

Curve No. 1, theoretical efficiency of boiler as a heat absorber at temperature below, is relative only; it is probably as a whole either too high or too low, and the various points of it may be high or low

relative to one another, but it serves its general purpose—to show less complete combustion of the coals low in carbon-hydrogen ratio. The distance between this curve and the efficiency 72* curve is greater the lower the carbon-hydrogen ratio.

Four charts were made detailing groups A, B, D, and Y.

In group A the lines (fig. 42) representing per cent of rating, per cent of CO loss, and combustion-chamber temperature are parallel

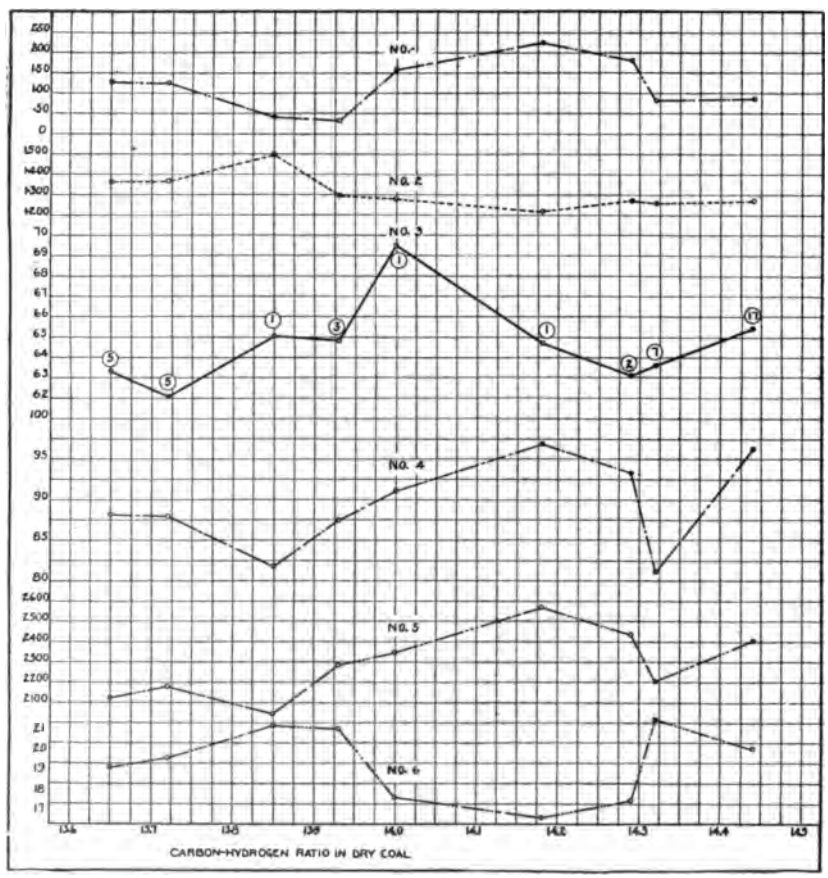

FIG. 42.—Coal classification based on carbon-hydrogen ratio as related to per cent of CO loss (curve No. 1); ratio of hydrogen to available hydrogen (curve No. 2); efficiency 72* (curve No. 3); per cent of rated capacity developed (curve No. 4); combustion-chamber temperature (° F.) (curve No. 5); and pounds of dry chimney gases per pound of "combustible" (curve No. 6). Group A, all values up to 14.5, dry coal.

to one another, and their slope is inverse, in a general way, to that of the lines representing hydrogen over available hydrogen and pounds of dry chimney gases per pound of "combustible." This group contains tests varying 13 per cent in efficiency, indicating the uncertainty of attaining the higher efficiency with coals of low carbon-hydrogen ratio. No other relations occur in this group such as occur in the higher groups.

Group B gives very marked relations. The lines (fig. 43) representing the per cent of rating, combustion-chamber temperature, per cent of CO loss, efficiency 72*, and per cent of clinker in refuse run in the same general direction and the values vary inversely with the pounds of dry chimney gases per pound of "combustible" and hydrogen over available hydrogen. Why the line for efficiency 72* should parallel the line of CO loss is not clear, especially as the latter

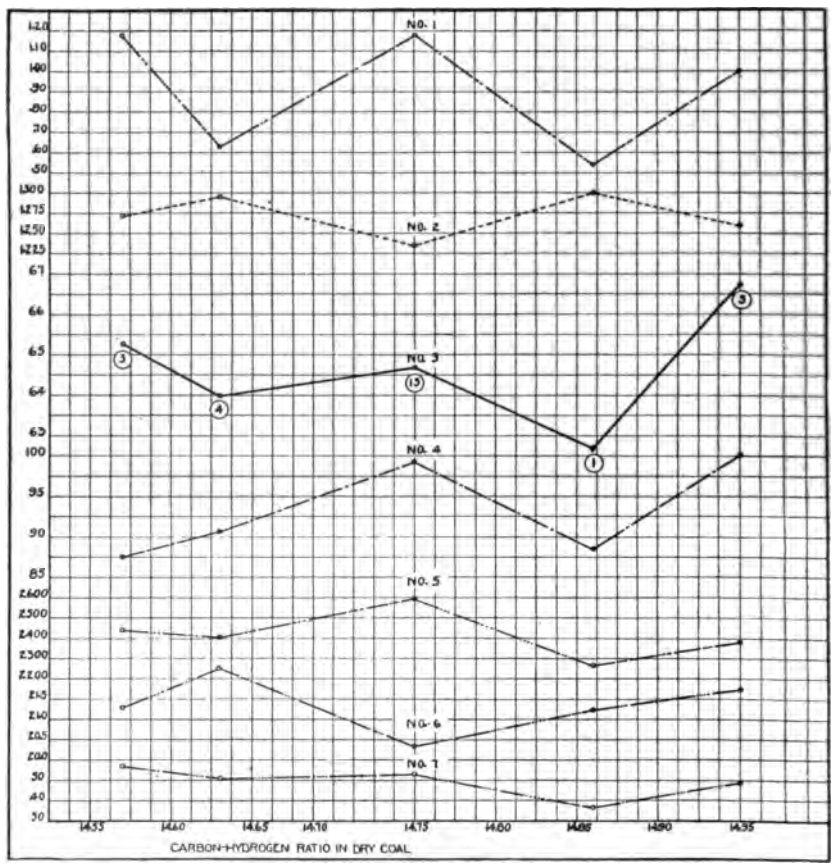

FIG. 43.—Coal classification based on carbon-hydrogen ratio as related to per cent of CO loss (curve No. 1); ratio of hydrogen to available hydrogen (curve No. 2); efficiency 72* (curve No. 3); per cent of rated capacity developed (curve No. 4); combustion-chamber temperature (° F.) (curve No. 5); pounds of dry chimney gases per pound of "combustible" (curve No. 6); and per cent of clinker in refuse (curve No. 7). Group B, values from 14.5 to 15.0, dry coal.

is high and the combustion-chamber temperature varies but little; however, not many tests are considered.

In group D (fig. 44) the lines representing the per cent of rating, combustion-chamber temperature, per cent of CO loss, and per cent of clinker in refuse are parallel to one another, and for the most part

that of hydrogen over available hydrogen follows the three in direction. The curves for efficiency and pounds of dry chimney gases per pound of "combustible" are parallel to each other and run inversely with all the rest.

The same characteristics appear in group Y (fig. 45) as in group D (fig. 44).

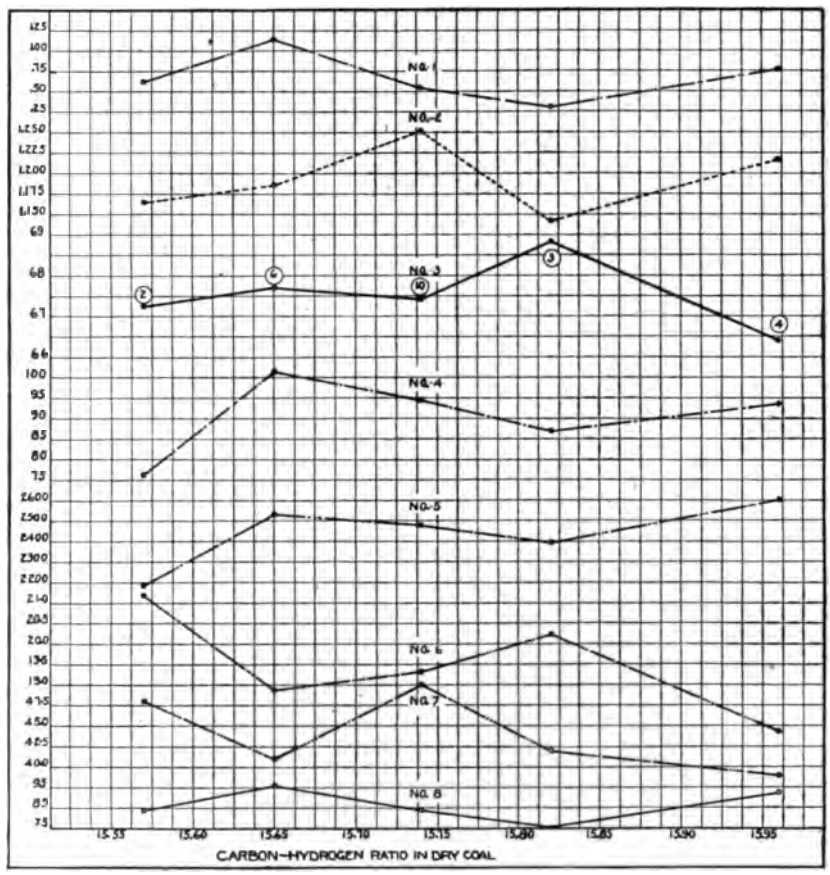

FIG. 44.—Coal classification based on carbon-hydrogen ratio as related to per cent of CO loss (curve No. 1); ratio of hydrogen to available hydrogen (curve No. 2); efficiency 72* (curve No. 3); per cent of rated capacity developed (curve No. 4); combustion-chamber temperature (° F.) (curve No. 5); pounds of dry chimney gases per pound of "combustible" (curve No. 6); per cent of clinker in refuse (curve No. 7); and average diameter of coal (curve No. 8). Group D, values from 15.5 to 16.0, dry coal.

Attempts were also made to classify coals according to the available hydrogen figured from the "combustible" in the coal; according to the ratio of carbon to available hydrogen, and according to the moisture over the per cent of air-drying loss. None of these were of much value.

CARBON-HYDROGEN RATIO IN COAL AS FIRED AS AFFECTING EFFICIENCY 72*.

Fig. 46 shows the effect of the carbon-hydrogen ratio of coal as received (fired) on efficiency 72* for each of three capacity groups. The curves determined by plotting efficiency 72* with carbon-hydrogen ratio for a nearly constant per cent of rating are very uniform.

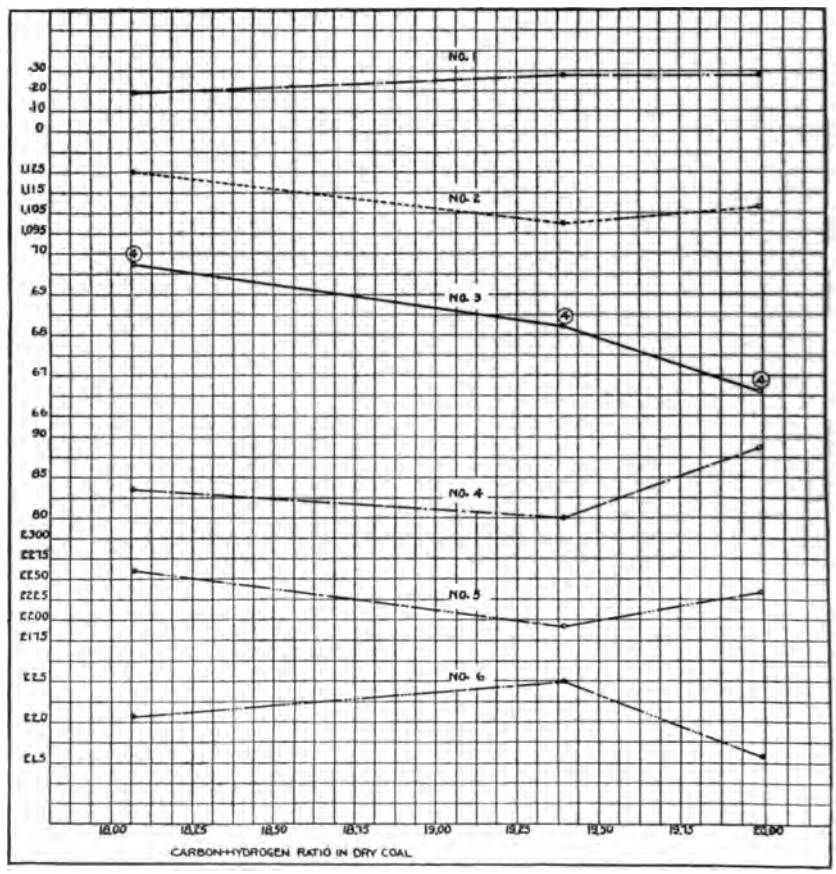

FIG. 45.—Coal classification based on carbon-hydrogen ratio as related to per cent of CO loss (curve No. 1); ratio of hydrogen to available hydrogen (curve No. 2); efficiency 72* (curve No. 3); per cent of rated capacity developed (curve No. 4); combustion-chamber temperature (° F.) (curve No. 5); and pounds of dry chimney gases per pound of "combustible" (curve No. 6). Group Y, values of 17.5 and over, dry coal.

Three curves were plotted, Nos. 1, 2, and 3, at capacities of 95 to 105, 85 to 95, and 75 to 85, respectively. The efficiency 72* range on any one curve decreases as the per cent of rated capacity decreases. A probable explanation of this chart is that, with the low carbon-hydrogen ratios, the efficient burning of coal is rather uncertain. As the capacity is increased the combustion-chamber temperature is raised; therefore the high-rating curves are the high-temperature curves. This relation probably has considerable to do with the

efficiency ranges on the three curves. It is also evident from this chart that the high capacities were obtained with the coals of low and medium carbon-hydrogen ratios.

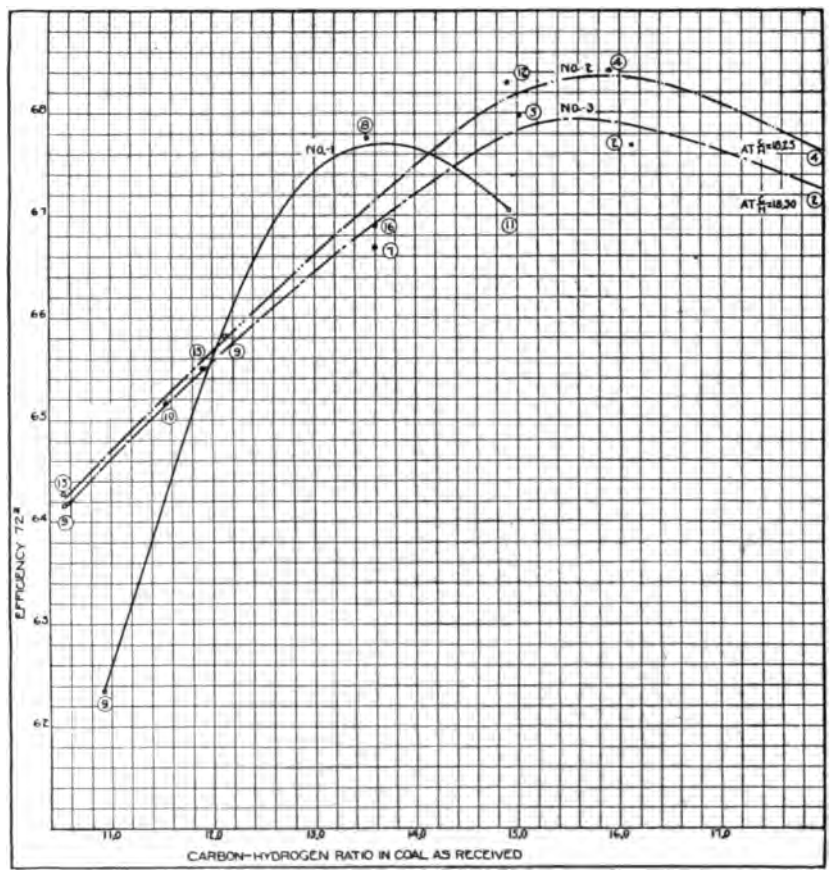

FIG. 46.—Coal classification based on per cent of rating. Efficiency curves: No. 1, from 95 to 105 per cent; No. 2, from 85 to 95 per cent; No. 3, from 75 to 85 per cent.

RELATION OF RATIO OF CARBON TO AVAILABLE HYDROGEN AND OF PER CENT OF AVAILABLE HYDROGEN TO EFFICIENCY 72*.

Fig. 47 is a graphic representation of efficiency 72* on the basis of ratio of carbon to available hydrogen. As this ratio increases there is a considerable increase in efficiency 72*, but the curve is very irregular. Curves Nos. 1 and 2 are similar, but are from two different series of tests. Curve No. 3 is a representation of efficiency 72* on an available hydrogen basis. The efficiency varies but little over the entire range of available hydrogen ratio.

The subjoined table shows two classifications based on the ratio of per cent of "volatile carbon"[a] to per cent of total carbon. The

[a] For definition of "volatile carbon" see glossary (p. 183). For information on the "volatile carbon" of coals see *Parr, S. W., Bull.* Illinois Geol. Survey No. 3, Urbana, Ill.

first (column 1) gives average efficiency 72* for average ratio of volatile carbon to total carbon values, showing that for the low ratio values we have the high efficiency 72* values and vice versa. There is, however, as the chart (fig. 48) shows, no uniformity of drop in efficiency as the value of the ratio increases. The second classification (columns 2–7) gives the values of average efficiency 72*

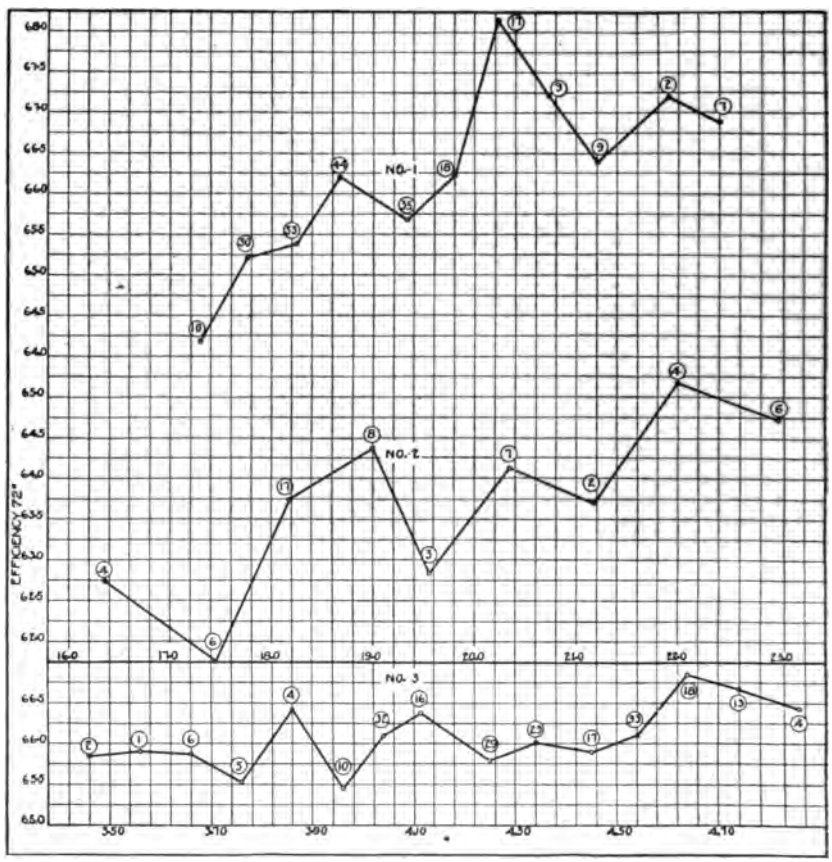

FIG. 47.—General curves showing classification of tests: No. 1 (tests 120–380) and No. 2 (tests 1–78), based on ratio of carbon to available hydrogen; No. 3 (tests 120–380), based on available hydrogen.

for the average values of the volatile carbon to total carbon, grouping them according to the number of B. t. u. supposedly evolved per square foot of grate surface per hour, and shows the same general relations as the preceding classification. The explanation may be that coals high in the ratio of volatile carbon to total carbon are harder to burn than those in which that ratio is low.

Classifications of efficiency 72 on basis of average ratio of volatile carbon to total carbon.*

Range of average ratio.	First classification—not grouped.	Second classification—grouped according to 10,000's of B. t. u. supposedly evolved per square foot of grate surface per hour.					
		Under 22.	22 to 24.	24 to 26.	26 to 28.	28 to 30.	30 and over.
	1.	2.	3.	4.	5.	6.	7.
Under 15:							
Number of tests	16	6	6	1	2	1	.....
Average ratio × 100	7.25	8.06	8.87	8.97	6.41	2.56	.....
Average efficiency 72*	67.35	68.20	67.34	65.18	68.10	62.92	.....
From 15 to 17:							
Number of tests	3	1	1	.....	.....	.....	1
Average ratio × 100	15.94	16.14	16.65	.....	.....	.....	15.04
Average efficiency 72*	65.63	68.51	67.24	.....	.....	.....	61.13
From 17 to 19:							
Number of tests	1	.....	.....	.....	.....	1	.....
Average ratio × 100	18.75	.....	.....	.....	.....	18.75	.....
Average efficiency 72*	63.63	.....	.....	.....	.....	63.63	.....
From 19 to 21:							
Number of tests	5	1	1	2	1	.....	.....
Average ratio × 100	20.16	20.09	20.52	19.95	20.30	.....	.....
Average efficiency 72*	65.59	68.21	63.40	65.27	65.78	.....	.....
From 21 to 23:							
Number of tests	18	1	5	5	1	.....	.....
Average ratio × 100	22.18	21.97	22.24	21.85	22.10	.....	.....
Average efficiency 72*	64.97	67.08	67.27	68.06	65.06	.....	.....
From 23 to 25:							
Number of tests	28	.....	5	9	4	.....	.....
Average ratio × 100	24.08	.....	23.65	24.56	24.15	.....	.....
Average efficiency 72*	67.22	.....	68.83	67.19	69.32	.....	.....
From 25 to 27:							
Number of tests	52	6	10	10	4	11	3
Average ratio × 100	26.10	26.27	26.28	26.16	26.05	26.01	26.50
Average efficiency 72*	66.42	67.58	67.09	68.96	65.84	64.70	66.51
From 27 to 29:							
Number of tests	63	7	5	14	7	7	6
Average ratio × 100	27.91	28.05	27.76	27.84	27.91	27.47	27.90
Average efficiency 72*	65.64	66.98	66.33	66.08	65.49	65.43	63.76
From 29 to 31:							
Number of tests	33	4	4	3	8	1	4
Average ratio × 100	29.94	29.54	30.25	29.86	29.82	30.03	30.28
Average efficiency 72*	63.87	66.48	66.55	63.86	64.12	61.70	61.17
From 31 to 33:							
Number of tests	37	6	11	13	2	4	.....
Average ratio × 100	31.86	31.69	31.94	31.86	31.46	31.81	.....
Average efficiency 72*	64.70	66.05	64.67	64.64	61.71	65.16	.....
From 33 to 35:							
Number of tests	10	1	2	4	.....	2	1
Average ratio × 100	33.82	34.32	33.89	33.89	.....	33.78	33.03
Average efficiency 72*	62.96	62.18	59.55	64.71	.....	63.83	61.88
Over 35:							
Number of tests	9	.....	1	1	2	.....	5
Average ratio × 100	36.81	.....	35.15	38.38	35.17	.....	37.23
Average efficiency 72*	58.14	.....	60.25	61.37	61.70	.....	55.95

RATIO OF HYDROGEN TO AVAILABLE HYDROGEN.

The ratio of hydrogen to available hydrogen was computed on about 200 ultimate analyses of dry coals using boiler-test samples (see fig. 49). This ratio and also the ratio of carbon to available hydrogen were suggested by Fred M. Stanton, of the chemical laboratory of this plant. These ratios were grouped according to values, as follows: Group R, all values up to 11.0; group S, from 11.0 to 12.0; group T, from 12.0 to 13.0; group U, from 13.0 to 14.0; and group V, 14.0 and over.

Curves showing the relations between the ratio of hydrogen to available hydrogen and efficiency 72*, per cent of rated capacity, per cent of CO loss, and combustion-chamber temperature were obtained by

averaging the total number of values for each of these ratio groups and plotting this average against the average of the ratios for the corresponding groups. The resulting efficiency line shows a gradual fall with an increase of the ratio of hydrogen to available hydrogen. The per cent of CO loss shows a gradual increase in value. The lines for per cent of rated capacity and combustion-chamber temperature are parallel and have maximum points where the ratio of hydrogen to available hydrogen has a value of about 1.25, this being the middle of the values for ratio of hydrogen to available hydrogen. The efficiency seems to be independent of both per cent of rating attained and combustion-chamber temperature. The range of efficiency for each group is shown by the figures near each point of the efficiency line. The range decreases, as in the other classifications, as the region of better coals is approached; likewise the best tests of all groups are about equally good.

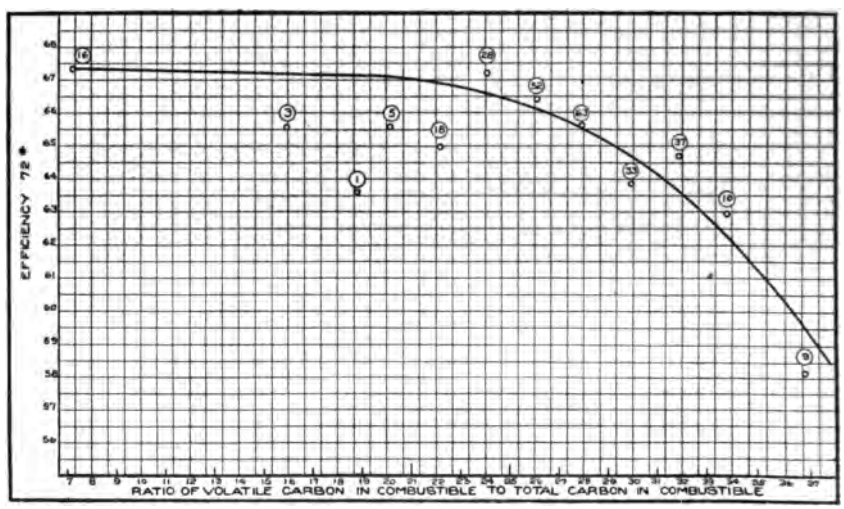

FIG. 48.—Relation between the ratio of volatile carbon to total carbon and efficiency 72*; tests 120-400.

Classifications have also been made on the following bases:

Per cent of sulphur from ultimate analysis of dry coal. (See fig. 28, p. 43.)
Per cent of ash in coal as fired. (See fig. 27, p. 41.)
Per cent of volatile matter in the "combustible." (See fig. 50, p. 89.)
Per cent of "fixed carbon," proximate analysis of coal as fired. (See fig. 51, p. 91.)
Per cent of free moisture, proximate analysis of coal as fired. (See fig. 22, p. 33.)
Per cent of ash, ultimate analysis of dry coal. (See fig. 26, p. 40.)
Per cent of oxygen in "combustible." (See fig. 52, p. 92.)
B. t. u. per pound of dry coal. (See fig. 53, p. 93.)

A study of the classifications of the ratios of carbon to hydrogen and hydrogen to available hydrogen and of single items from the proximate analysis of coal as fired and also the ultimate analysis of *dry coal* reveals the fact that while the points determining the curves

of efficiency 72* on the ratio bases fall rather uniformly on the curves, certain peculiarities are averaged out, as shown by the small variation of efficiency values over the entire range of the ratio. The classifications based on separate items from the chemical analysis of the coal give a much wider range of efficiency 72*.

The most valuable classification seems to be the one based on per cent of "fixed carbon" from the proximate analysis of the coal as fired.

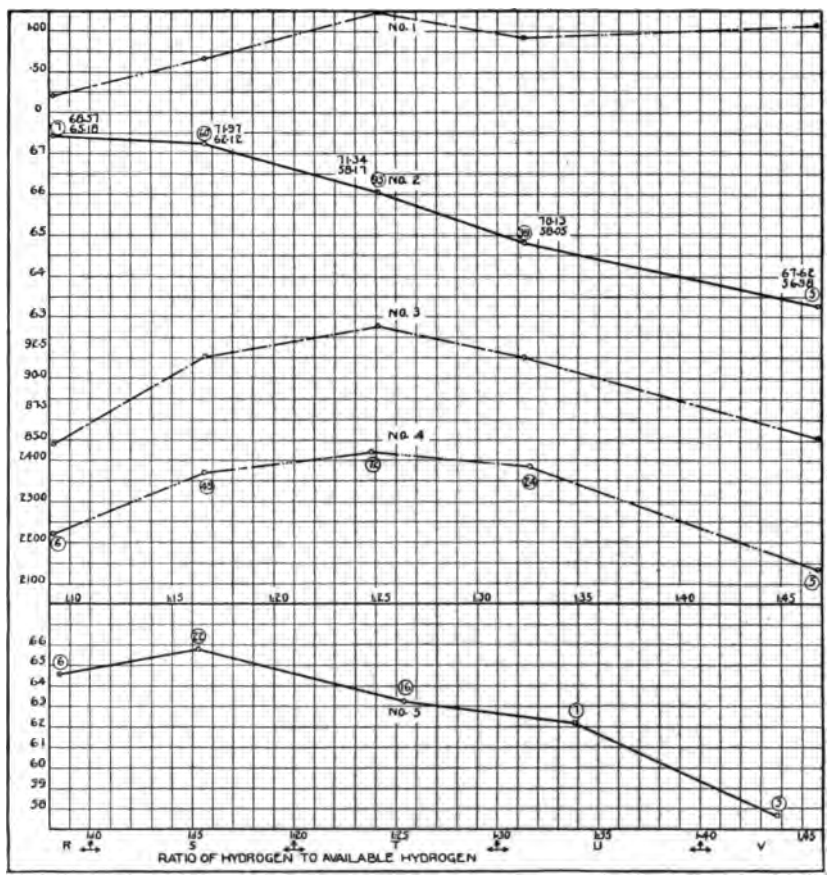

FIG. 49.—Coal classification based on ratio of hydrogen to available hydrogen as related to per cent of CO loss (curve No. 1); efficiency 72*, tests 124-380 (curve No. 2); per cent of rated capacity developed (curve No. 3); combustion-chamber temperature (°F.) (curve No. 4); and efficiency 72* (tests 1-78, excluding tests on washed and briquetted coals) (curve No. 5).

(See fig. 51.) A classification nearly as good, and giving a little larger range of efficiency is that based on per cent of "volatile matter" in the "combustible." (See fig. 50.) The practical value of a classification for estimating the efficiency 72* at which a coal can be burned depends largely on the ease with which the item on which the classification is based can be determined. Both per cent of "fixed carbon" and per cent of "volatile matter" are obtained from

a proximate analysis of coal, which can be made with very little difficulty.

The reason for deciding on fixed carbon in coal as fired in preference to volatile matter in "combustible" was based on a comparison of the curves for combustion-chamber temperature on figs. 50 and 51. With the exception of the two end points, all the curves of fig. 51 are fairly regular.

The subjoined classification of efficiency 72* on a basis of carbon-hydrogen ratio in dry coal for varying ranges of combustion-chamber temperature is but a subdivision of the carbon-hydrogen averages shown on fig. 25 (p. 37). It was thought that for any single carbon-hydrogen ratio group the efficiency 72* might increase or decrease with an increase of combustion-chamber temperature. However, after the tests have been separated according to combustion-chamber temperatures there are so few points in each grouping that any conclusion would be unreliable.

The tabulation shows the familiar general relation of increase of efficiency 72* as the carbon-hydrogen ratio increases. Nothing else is shown.

Classification of efficiency 72 on basis of carbon-hydrogen ratio in dry coal.*

	Carbon-hydrogen ratio in dry coal.								
	13.5 to 14.	14 to 14.5.	14.5 to 15.	15 to 15.5.	15.5 to 16.	16 to 16.5.	16.5 to 17.	17 to 18.	18 up.
Temperature range 1,900° to 2,200° F.:									
Number of tests	8	3	4	6	1	4	2	2	7
Average carbon-hydrogen ratio in dry coal	13.75	14.33	14.83	15.17	15.55	16.31	16.67	17.48	20.39
Average efficiency 72*	63.85	63.61	66.16	64.36	65.95	64.18	67.18	68.18	67.56
Temperature range 2,200° to 2,300° F.:									
Number of tests	2	5	7	3	5	8	2	2	2
Average carbon-hydrogen ratio in dry coal	13.66	14.40	14.80	15.12	15.71	16.06	16.71	17.04	19.35
Average efficiency 72*	61.79	65.03	61.71	66.26	66.25	66.74	66.32	67.88	67.76
Temperature range 2,300° to 2,400° F.:									
Number of tests	2	12	6	7	5	4	1	.....	4
Average carbon-hydrogen ratio in dry coal	13.84	14.39	14.68	15.15	15.72	16.35	17.93	.....	19.47
Average efficiency 72*	63.00	65.63	65.88	64.60	64.12	68.61	67.94	.....	66.48
Temperature range 2,400° to 2,500° F.:									
Number of tests	3	6	5	11	6	10	2	.....	2
Average carbon-hydrogen ratio in dry coal	13.78	14.42	14.81	15.16	15.70	16.29	16.67	.....	20.42
Average efficiency 72*	61.62	63.83	66.61	66.00	66.13	67.61	64.59	.....	66.84
Temperature range 2,500° to 2,600° F.:									
Number of tests	.....	4	4	5	8	1	2	.....	.....
Average carbon-hydrogen ratio in dry coal	.....	14.33	14.73	15.22	15.81	16.14	16.69	.....	.....
Average efficiency 72*	.....	64.54	65.44	65.88	67.45	65.77	69.06	.....	.....
Temperature range 2,600° to 2,900° F.:									
Number of tests	.....	2	9	4	7	.....	2	.....	.....
Average carbon-hydrogen ratio in dry coal	.....	14.31	14.75	15.24	15.68	.....	16.64	.....	.....
Average efficiency 72*	.....	62.35	64.96	63.33	68.64	.....	68.77	.....	.....

PER CENT OF "VOLATILE MATTER" IN THE "COMBUSTIBLE."

The curves of fig. 50 are based on about 300 tests made on coals from all parts of the United States, classified according to the percentage of "volatile matter" in the "combustible," considering as "combustible" that portion of the coal which remains after taking out the moisture and ash as determined by the proximate analysis. As stated elsewhere the word "combustible" is really a misnomer.

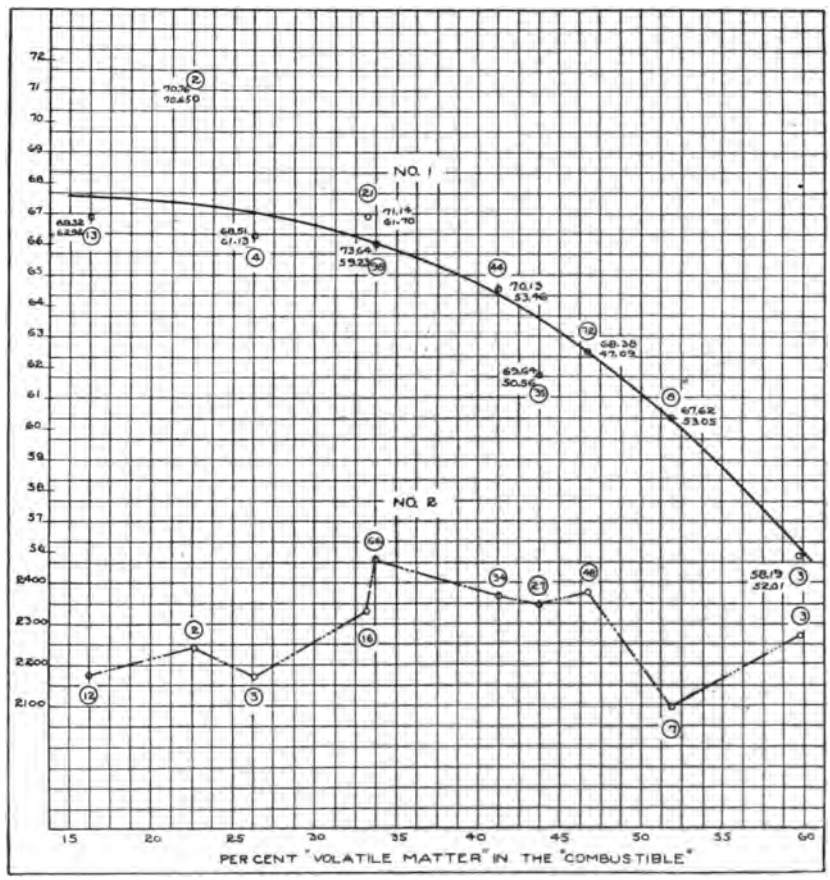

FIG. 50.—Relations of per cent of "volatile matter" in the "combustible" to efficiency 72* (curve No. 1) and combustion-chamber temperature (°F.) (curve No. 2). Tests 101–400.

The proximate analysis is also capable of considerable variation, but nevertheless it gives a clew.

Curve No. 1 is similar to many obtained by other investigators. It means that one should beware of a high percentage of "volatile matter," but not necessarily that a coal of high volatile matter is poor, for a great deal depends on the composition of the coal, inasmuch as coals break down very differently on heating. It has been

noted that, in general, the coals of high volatile matter have some other undesirable features, such as high ash content. The most important thing to emphasize is that even with a good furnace the coals high in volatile matter are at a slight disadvantage.

Curve No. 2 shows that the combustion-chamber temperature rises with the volatile matter of coal up to about 38 per cent and then drops. The rise of the temperature is due to the fact that the volatile matter of the coal is driven off the fuel bed and burns in the combustion chamber, so that the temperature of the gases of combustion is measured before the heat is dissipated from them. The rise is also due to the increased rate of combustion. As the volatile matter increases the coal burns more rapidly and less air is used to burn 1 pound of combustible. Beyond 38 per cent of volatile matter the coals become high in ash and moisture; in fact all the lignites are classed among the coals at the right-hand end. Both the ash and moisture reduce the combustion-chamber temperature. The high ash causes a slower rate of combustion and consequently more air is used per pound of combustible. The moisture lowers the temperature directly by its high specific heat. Work on the constitution of the cellulose derivatives of coals, now being prosecuted at this plant and at several other places, should give some valuable information on such practical questions as these. The customary "proximate analysis" is only an empirical method and can be expected to give nothing more than clews; much more is to be expected from ultimate analyses.

As in all other curves of this bulletin the small numbers, by the points, indicate the number of tests and the four-place numbers indicate the highest and lowest efficiencies of each group.

FIXED CARBON (PROXIMATE ANALYSIS).

The chart shown in fig. 51 (p. 91) is one of a series based on the "proximate analysis" of "coal as fired." It is realized that such an analysis is purely empirical and capable of giving results varying considerably; nevertheless it is of some value.

Curve No. 1 shows a general rise of efficiency up to a "fixed carbon" content of 60 per cent and perhaps an inclination to fall off past that point. This 60 per cent point is roughly the place of maximum B. t. u. value per pound of moist coal. The numbers inclosed in circles show the number of tests falling in each group.

Curve No. 2, per cent of rated capacity developed, is practically uninfluenced.

Curve No. 3, combustion-chamber temperature, shows a general tendency to rise and has a hump in the middle. This is perhaps explained by the fact that the coals low in fixed carbon are of poor grade—high in ash and moisture—and for that reason it is difficult

to get a hot fire with these coals. With coals high in fixed carbon nearly all of the combustion takes place in the fuel bed, so that the gases have cooled considerably by the time they reach the rear of the furnace. These coals also burn slowly and therefore require more air for combustion. The coals of moderate fixed carbon give a long, hot, luminous flame.

It is stated elsewhere in this bulletin that the capacity is a function

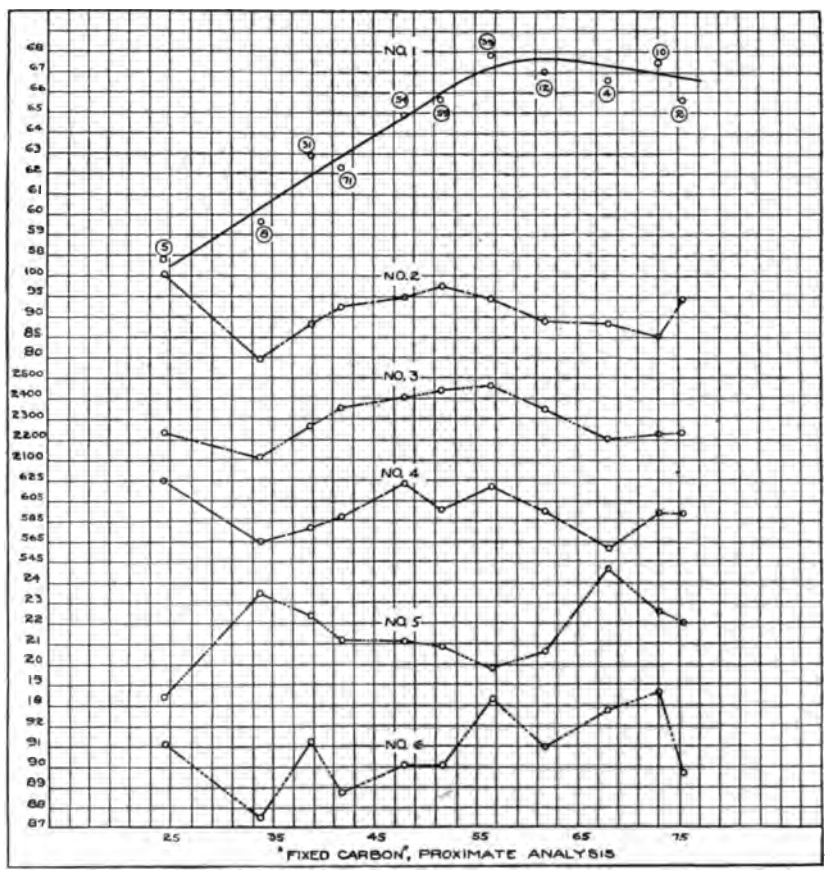

FIG. 51.—Relations of "fixed carbon" to efficiency 72* (curve No. 1); per cent of rated capacity developed (curve No. 2); combustion-chamber temperature (°F.) (curve No. 3); flue-gas temperature (°F.) (curve No. 4); pounds of dry chimney gases per pound of "combustible" (curve No. 5); and per cent completeness of combustion (E_3) (curve No. 6). Tests 89-401.

of initial temperature of the furnace gases. This is plainly shown by curves Nos. 2 and 3, which are parallel.

Curve No. 4, flue-gas temperature, is closely parallel to No. 3. This is only another illustration of the fact that with the boilers of this plant flue temperatures increase with furnace temperatures, and, so far as the authors can see, it must be so with all boilers, even when liberating the same quantity of heat in the furnace per second with various percentages of air excess. (See p. 24.)

Curve No. 5 shows the pounds of dry chimney gases per pound of "combustible." It is very little affected, tending to rise with the "fixed carbon." It varies inversely with furnace and flue temperatures.

Curve No. 6 shows the per cent of completeness of combustion, being the percentage of the heat of the combustible which was actually generated. It rises with increase of "fixed carbon" and its value of about 90 per cent indicates a wide margin for improvement.

RELATION OF EFFICIENCY 72* TO PER CENT OF OXYGEN IN "COMBUSTIBLE."

The chart shown in fig. 52 contains two curves plotted on the same data. The upper one was obtained by classifying the tests according to code "boiler efficiency" (72*) and the lower by classify-

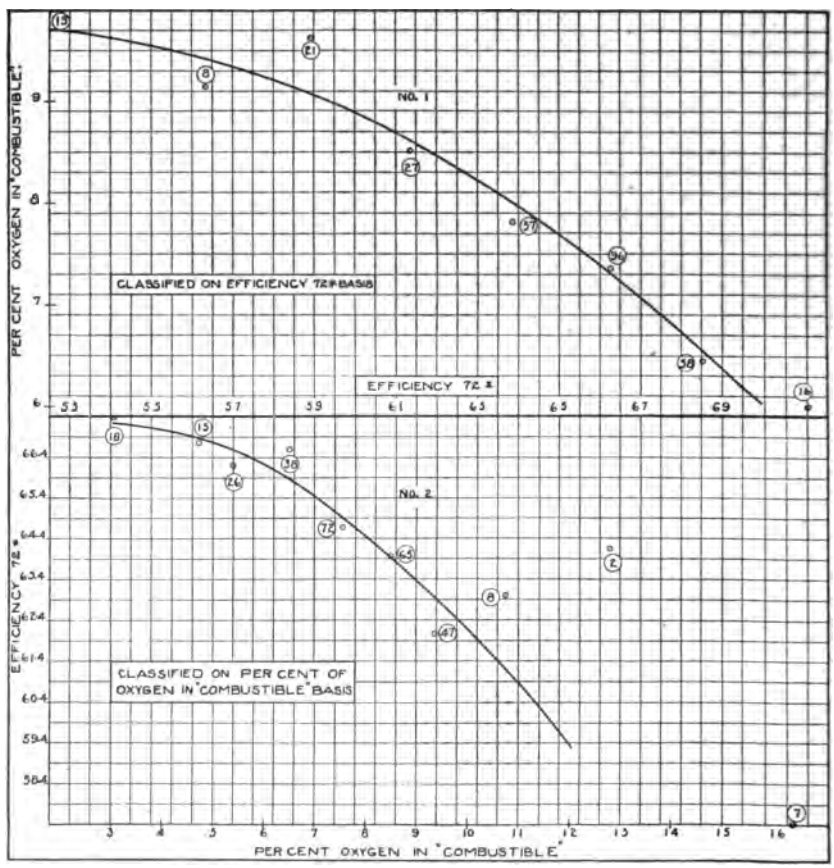

FIG. 52.—Relation of efficiency 72* to per cent of oxygen in "combustible," classified on each as a basis. Tests 101-400.

ing them according to the per cent of oxygen in the "combustible." By the "combustible" is meant what is left of the coal after taking out the moisture, sulphur, and ash. This remnant has been designated as "pure coal," which is preferable to calling it "combustible."

Both curves show unmistakably that somehow the oxygen of the coal, which is chemically combined, exerts a harmful influence. It seems plausible that there is nothing inherent in the presence of oxygen in a coal molecule which makes it impossible to break it down and burn it as well as any molecule lacking oxygen. This assumption puts the blame on our furnaces.

This chart is in agreement with that of fig. 33 (p. 56), which presents a classification of several items on a smoke basis. The "unaccounted-for" loss, CO loss, and per cent of oxygen all rise with the increase of smoke and the efficiency falls very slightly.

BRITISH THERMAL UNITS PER POUND OF DRY COAL.

The curves of fig. 53 are based on 296 tests made on coals from all parts of the country. In general, the eastern coals fall on the

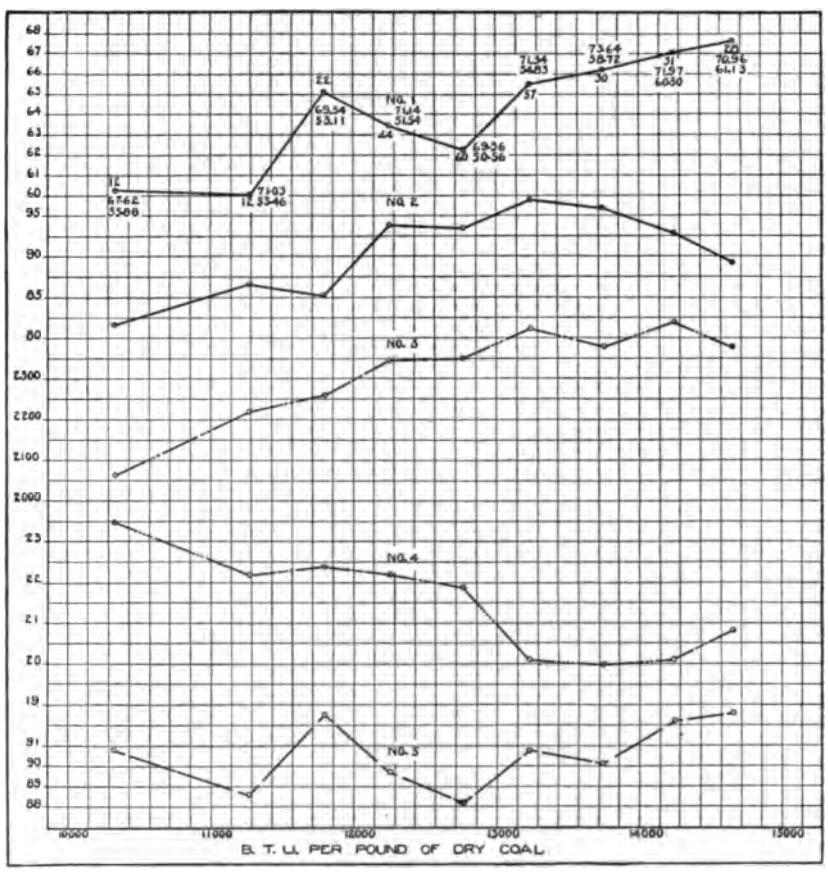

FIG. 53. Relations of B. t. u. value of dry coal to boiler efficiency 72* (curve No. 1); per cent rated capacity developed (curve No. 2); combustion-chamber temperature (° F.) (curve No. 3); pounds of dry chimney gases per pound of "combustible" (curve No. 4); per cent completeness of combustion (E_3) (curve No. 5). Tests 89–400.

right and the lignites on the left part of the curve. On curve No. 1 *the small number* near each point gives the number of tests

falling in that B. t. u. group. Each of the other four curves below is based on the same number of tests in the various groups. The four-place numbers in pairs on curve No. 1 indicate the highest and lowest efficiencies 72* falling in each group. It will be noted that the highest efficiencies are nearly as good in the left groups as in the right, indicating that it is possible to burn coals of low heating value as efficiently as high-grade coals. The increase of average efficiencies is only about 7 per cent for the range of 5,000 B. t. u.

The average capacity, as shown by curve No. 2, rises considerably as the coal improves in heating value. Perhaps most of the low B. t. u. coals could be made to furnish as much steam if burned on a larger grate. If the coal did not clinker seriously, the use of a rocking grate would increase the capacity. On some coals the use of the automatic stoker might give better results.

Curve No. 4, pounds of dry chimney gases per pound of "combustible," descends with the better coals, partly because they are usually more manageable on the fuel bed and because they seem to break down on heating with evolution of gaseous compounds easier to burn, on which account the air supply can be reduced with safety.

Curve No. 5 gives the average "furnace efficiency," or, better, the per cent of completeness of combustion. These calculated efficiencies are only approximate.

RATIO OF ASH TO SULPHUR IN DRY COAL.

It is sometimes said that although sulphur in coal does not of itself materially reduce the value of the coal for steam making, a low percentage of ash with a high percentage of sulphur is apt to make trouble. To test this possibility a classification was made of many tests on many coals, the tests being grouped according to the ratio of total ash to sulphur. The corresponding values of the averages of efficiencies 72* are practically constant.

As a check on this work a classification was also made of the ratio of ash to sulphur in dry coal on an efficiency 72* basis. As the efficiency 72* increases there is practically no change in the value of the ash to sulphur ratio. (See figs. 21, p. 30, and 28, p. 43.)

A table of efficiencies 72* classified on the basis of per cent of ash plus sulphur in dry coal shows little variation between the average efficiency values for the several groups. Tables showing the three classifications follow:

Classification of efficiency 72 on basis of ratio of ash to sulphur in dry coal.*

	Ratio of ash to sulphur.								
	0 to 2.5.	2.5 to 5.0.	5.0 to 7.5.	7.5 to 10.	10 to 15.	15 to 20.	20 to 25.	25 to 30.	Over 30.
Number of tests	27	106	73	27	8	17	9	4	4
Average ratio of ash to sulphur	2.23	3.29	6.06	8.69	12.10	17.11	22.64	26.46	33.29
Average efficiency 72*	64.83	64.57	66.45	66.09	65.76	64.67	64.96	65.98	66.26

Classification of ratio of ash to sulphur in dry coal on basis of efficiency 72.*

	Efficiency 72*.											
	Up to 53.	53 to 57.	57 to 59.	59 to 62.	62 to 63.	63 to 64.	64 to 65.	65 to 66.	66 to 67.	67 to 68.	68 to 69.	69 and over.
Number of tests	1	5	12	26	15	19	28	43	32	36	25	34
Average efficiency 72*	52.01	55.49	58.20	60.62	62.49	63.45	64.44	65.54	66.41	67.47	68.38	70.18
Average ratio of ash to sulphur in dry coal	16.27	6.24	5.77	6.61	4.40	7.67	4.81	8.82	6.31	7.30	6.51	8.64

Classification of efficiency 72 on per cent of ash plus sulphur in dry coal (Indiana, Illinois, and western Kentucky coals).*

	Per cent of ash plus sulphur.								
	Up to 9.	9 to 11.	11 to 13.	13 to 15.	15 to 17.	17 to 19.	19 to 21.	21 to 23.	23 up.
Number of tests	3	13	7	16	14	14	8	12	5
Average per cent of ash plus sulphur in dry coal	7.40	10.38	11.95	14.14	15.98	18.12	20.02	21.90	24.83
Average efficiency 72*	66.00	65.73	68.03	63.44	64.73	64.10	65.47	66.33	66.47

SUGGESTED STEAM-TURBINE CYCLES, HEAT ABSORPTION, AND BOILER EFFICIENCIES.

THE BOILER AND THE FURNACE AND THEIR EFFICIENCIES.

The boiler with its setting consists mainly of two parts, the furnace and the boiler proper. The furnace is the heat generator and the boiler the heat absorber. In practice both are imperfect in their functions. A perfect furnace would burn the fuel completely. A perfect boiler would absorb all the heat evolved in the furnace provided the temperature of the water in the boiler was that of the atmosphere. It follows, then, that the furnace efficiency is the ratio of the heat evolved in the furnace to the potential heat of the fuel fired, and that the boiler efficiency is the ratio of the heat absorbed by the boiler to the heat evolved in the furnace; the combined efficiency of the furnace and boiler being the ratio of the heat absorbed by the boiler to the potential heat of the fuel fired. The grate is taken as a part of the furnace. The true boiler efficiency is the ratio of the heat absorbed to the heat which is available to the boiler, this available heat being that portion of the heat in the furnace gases which is above the temperature of the steam.

If the wording in the above definitions is somewhat changed another set of efficiencies is obtained, which may be called the thermodynamic efficiencies. The efficiency of the furnace is the ratio of the heat made available to the boiler to the potential heat of the fuel fired. The efficiency of the boiler is the ratio of that portion of the heat absorbed which is available for power purposes (engine or tur-

bine) to the heat available to the boiler. The combined efficiency of the furnace and boiler is the ratio of the heat made available for power purposes to the heat value of the fuel fired. The fact is that the steam engine is usually blamed for wasting heat which is not available to it.

To illustrate the above definitions let the various heat values be represented by diagrams. For the representation of the heat in the furnace a diagram such as given in *A*, fig. 54, can be used. This diagram has absolute temperature for the ordinates, and a factor proportional to the specific heat of the furnace gases multiplied by their weight as abscissas. In the same chart (fig. 54, *B*) is an ideal cycle of a steam engine or turbine plotted on temperature-entropy

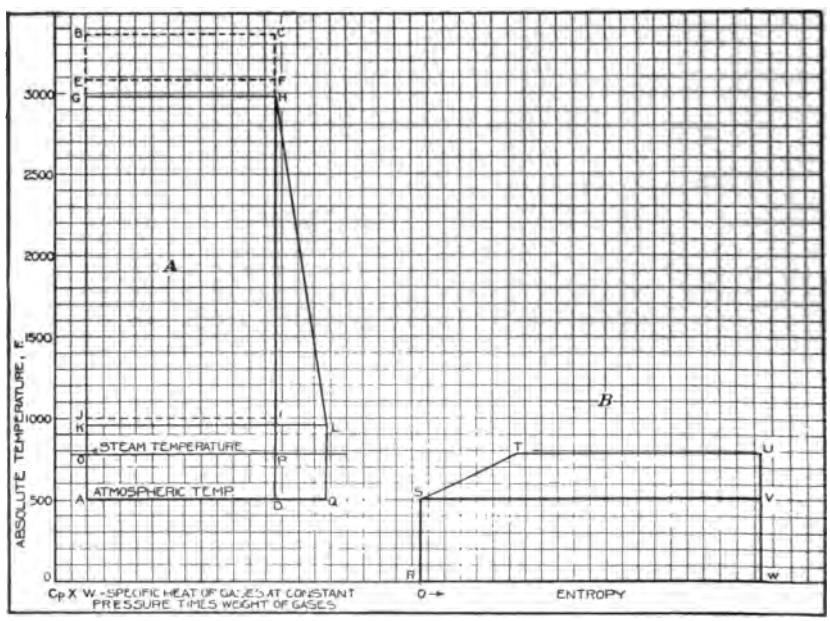

FIG. 54.—Temperature-entropy diagrams for boiler: *A*, For air and coal; *B*, for water and steam.

plane. It must be understood that the abscissas of these two diagrams are in different units. The abscissa in *B* is taken in entropy units because the adiabatic expansion and the availability of heat to the steam engine or turbine can be best shown by temperature-entropy diagrams.

On the assumption that 1 pound of combustible is completely burned, the various quantities of heat in the furnace are represented in *A* as follows: The area ABCD represents the potential heat in the fuel and also the heat developed in the furnace. The heat available for the boiler, represented in the diagram by the area OBCP, is the heat above the temperature of the steam and is the limit of the heat which the boiler can absorb. The remainder of the heat, repre-

sented by the area AOPD, is below the temperature of the steam and therefore can not be absorbed by the boiler.

In *B* the area RSTUW represents the heat absorbed by the boiler and delivered to the engine. Of this heat only a portion, represented by the area STUV, is available for the engine to be converted into mechanical energy. The remainder of the heat, represented by the area RSVW, is below the atmospheric temperature and can not be converted by the steam engine into mechanical energy. It may be said here that the limit for adiabatic expansion of steam in a steam engine or turbine is set by the temperature of the cooling water in the condenser. However, as the cooling water is nearly at the temperature of the atmosphere, the atmospheric temperature may be taken as the limit. It is entirely out of the question to obtain lower pressure in a condenser than that corresponding to the steam temperature equal to the temperature of the cooling water, no matter how perfect the air pump may be. For this reason it is said that the heat which is left in steam after it has been expanded adiabatically to the temperature of the atmosphere is below the atmospheric temperature. Of course this reasoning does not apply to a case where the steam is used for heating purposes.

During the process of transmitting the heat from the boiler furnace to the engine, the heat loses much of its availability, the greatest drop being in the transmission of the heat from the furnace gases into the boiler water. During this transmission there is a great drop in temperature, and with it drops the availability.

To show what efficiency could be obtained from an ideal steam-generating outfit and a steam engine working on a perfect cycle, as shown in *B*, fig. 54, an example is given below:

Suppose that 1 pound of "combustible" of the coal of test No. 204 is burned with 18.3 pounds of air in a perfect furnace. The heat value of 1 pound of this "combustible" is 14,660 B. t. u., and if we assume the atmospheric temperature to be 50° F. and the steam pressure 80 pounds by gage, the various heat quantities are as follows: Heat evolved in furnace, 14,660 B. t. u.; heat available for boiler, 13,320 B. t. u. The remaining portion of the heat evolved in the furnace is below 324° F., the temperature of the steam, and is either in the gases or in the moisture formed by burning the hydrogen of the "combustible." As this is an ideal case, all the heat which is available to the boiler is absorbed by it. On the assumption that there is no radiation from the boiler and the pipe connections, the heat delivered to the engine is 13,320 B. t. u. Of this heat only 4,056 B. t. u. is available for the engine. This last quantity can be obtained from a steam table (such as Reeve's) in the following manner:

The total heat of 1 pound of saturated steam at 80 pounds gage pressure is 1,180.3 B. t. u., and the entropy is 1.5976. Within the limit this

steam can be expanded to atmospheric temperature, which in this assumed case is 50° F. The corresponding absolute pressure of steam is given in the table as 0.36 inch of mercury. The total heat of 1 pound of steam at this pressure is 1,096.8 B. t. u. and the entropy 2.1478. The heat of 1 pound of water at 50° F. is 18.08 B. t. u., and the entropy is 0.0360 in the table, the heats and entropies being counted from feed water at 32° F.

As the temperature of the feed water is nearly that of the atmosphere, which in the assumed case is 50° F., the heats and entropies used in this problem are counted from feed water at 50° F. These heats and entropies can be obtained by subtracting from the values given in the table the heat and entropy of water at 50° F. Inasmuch as with adiabatic expansion the entropy remains constant, the quality of the steam at the end of the expansion of steam from 80 pounds gage to 0.36 inch of mercury absolute pressure is:

$$\frac{1.5976-.0360}{2.1478-.0360}=\frac{1.5616}{2.1118}=74 \text{ per cent dry.}$$

The heat left in 1 pound of steam at the end of the expansion is

$$(1{,}096.8-18.08)\times .74=797.1.$$

The total heat left in the steam at the end of the expansion when $\frac{13{,}320}{1{,}180.3-18.08}$ pounds of steam is used is

$$\frac{13{,}320}{1{,}180.3-18.08}\times 797.1=9{,}264.1.$$

Then the heat converted into work is $13{,}320-9{,}264.1=4{,}056$ B. t. u.

In this case the heat in the condensed steam does not enter into the computation because it is at the temperature of the feed water.

In the example just given the various efficiencies are as follows: Furnace efficiency = 14,660 ÷ 14,660 = 100 per cent; boiler efficiency = 13,320 ÷ 14,660 = 90.9 per cent; boiler and furnace efficiency = 13,320 ÷ 14,660 = 90.9 per cent; true boiler efficiency = 13,320 ÷ 13,320 = 100 per cent. The thermodynamic efficiencies are: Furnace efficiency = 13,320 ÷ 14,660 = 90.9 per cent; boiler efficiency = 4,056 ÷ 13,320 = 30.45 per cent; efficiency of furnace and boiler = 4,056 ÷ 14,660 = 27.67 per cent.

Of course by means of the economizer and by using superheated steam these ideal efficiencies could be somewhat raised. Steam boilers are not as efficient for power purposes as the figures obtained from boiler trials ordinarily imply.

In the above discussion only the limiting case was considered. In practice there are many losses which reduce the boiler efficiency to less than two-thirds and the total efficiency of the steam outfit to less than one-half.

As the process of heat evolution and heat transmission goes on in the furnace and the boiler the principal sources of loss are about as follows:

(*a*) Part of the combustible drops through the grate into the ash pit and is not burned.

(*b*) Part of the coal is gasified, and the gases escape before they are burned.

(*c*) Part of the heat evolved in the furnace is radiated through the fire doors and the furnace walls.

Of these three losses, the second is perhaps the most serious and increases rapidly after the content of CO_2 in the flue gases passes a certain limit. (See fig. 31, p. 51.) Losses *a* and *b* diminish the heat which is actually evolved in the furnace, and the temperature of the gases of combustion. In fig. 54 these losses are represented by the area EBCF. Loss *c* further decreases the heat which has already been evolved in the furnace. In the diagram this loss of heat is represented by the area GEFH.

(*d*) No boiler cools the furnace gases to the temperature of the steam; the gases leave the heating surface of the boiler at a temperature from 100° to 300° F. higher than that of the steam. The heat lost in the waste gases is represented by the area AJID.

(*e*) As the gases pass through the boiler setting cold air leaks in, lowers their temperature, and by increasing their weight increases the loss up the stack. The heat loss in the waste gases is then represented by the area AKLQ, and the loss due to the leakage of air is represented by the difference of the areas AKLQ and AJID.

(*f*) The total moisture (from the coal and air, the water of composition, and the moisture formed by the burning of the available hydrogen of the coal) lowers the temperature of combustion and with its high specific and latent heat increases the loss up the stack.

The heat value of the coal is represented by the total area ABCD, the heat actually evolved in the furnace by the area AEFD, the heat available to the boiler by the area JGHI, and the heat absorbed by the boiler, if there were no leakage of air, by the area JGHI. When air leaks into the setting the heat absorbed by the boiler is represented by the difference between the area AGHD and the area AKLQ.

In most of the commercial appliances for making steam the process of heat absorption begins before the process of heat evolution has been completed; in fact, the two processes go on together as soon as the temperature of the gases has risen sufficiently above the temperature of the steam. This is true to a great extent with all furnaces having no clay-tile roof and no combustion chamber and with all internally fired boilers. Even in a furnace of the Heine type a considerable portion of the heat is absorbed by the boiler through the tile roof. Such abstraction of heat necessarily reduces the final temperature of the products of combustion.

HIGH INITIAL FURNACE TEMPERATURE AND ITS EFFECT ON ECONOMY.

From what is said in the paragraphs on efficiencies it appears that more heat can be made available for the boiler if higher initial temperature and lower steam pressure be used. In general this proposition is true; however, both conditions have their limits beyond which new losses coming into play more than counterbalance the gain.

First let the relative gain and loss due to high initial temperature be considered. In order to obtain high initial temperature it is necessary to reduce the weight of gases per pound of "combustible." This condition means that less air is admitted into the furnace and less free oxygen is present in the gases. The reduction of free oxygen in the gases necessarily increases the amount of incomplete combustion, as shown in figs. 13 (p. 22), 14 (p. 23), and 31 (p. 51). The curve of fig. 31 indicates that the furnace efficiency drops very rapidly after the CO_2 content in the flue gas has reached about 9 per cent (perhaps 11 or 12 per cent in the furnace, before the gases have been diluted by leaks).

The loss up the stack is not reduced so much as the reduction of the weight of the gases per pound of "combustible" would indicate, because with the rise of the initial temperature the flue-gas temperature also rises. The curve of fig. 16 (p. 24) shows this relation of the flue-gas temperature to the initial (combustion-chamber) temperature.

To show that extremes either in high or low initial temperature may reduce the combined efficiency of the furnace and boiler, three cases were computed, and the results are given on page 101.

Suppose that the coal of test 204 is burned with three different furnace-gas compositions, having CO_2 contents of 7.0, 10.0, and 13.0 per cent, the respective percentages of completeness of combustion as obtained from the curve of fig. 31 will be 91.8, 90.5, and 86.4 per cent. To account for the loss in incomplete combustion the flue-gas analyses might be about as given below:

Hypothetical flue-gas analyses.

Gas.	Case 1.	Case 2.	Case 3.
CO_2	7.0	10.0	13.0
O_2	12.0	8.0	5.0
CO	.2	.4	1.0
CH_4	.15	.2	.4
H_2	1	.2	.3
C_2H_4	.05	.1	.2
N_2	80.5	81.1	80.1
	100.00	100.0	100.0

Except perhaps CO, all the combustible gases in all three cases are by ordinary methods undeterminable; it is simply assumed that they are present. The heat loss due to each combustible gas in the as-

sumed composition of flue gases is computed by the following general formulas:

(*a*) Loss due to CO =

$$\frac{28CO}{12\ (CO_2+CO+CH_4+2C_2H_4)} \times \left\{\begin{matrix}\text{per cent of carbon}\\ \text{in "combustible"}\end{matrix}\right\} \times 4{,}325.$$

(*b*) Loss due to CH_4 =

$$\frac{16CH_4}{12\ (CO_2+CO+CH_4+2C_2H_4)} \times \left\{\begin{matrix}\text{per cent of carbon}\\ \text{in "combustible"}\end{matrix}\right\} \times 23{,}510.$$

(*c*) Loss due to H_2 =

$$\frac{2H_2}{12\ (CO_2+CO+CH_4+2C_2H_4)} \times \left\{\begin{matrix}\text{per cent of carbon}\\ \text{in "combustible"}\end{matrix}\right\} \times 62{,}030.$$

(*d*) Loss due to C_2H_4 =

$$\frac{28C_2H_4}{12\ (CO_2+CO+CH_4+2C_2H_4)} \times \left\{\begin{matrix}\text{per cent of carbon}\\ \text{in "combustible"}\end{matrix}\right\} \times 21{,}340.$$

The number at the end of each formula is the heat value of 1 pound of that particular gas. The results obtained are in B. t. u.

The loss due to the presence of each gas in each of the three cases, together with the calculated results, is shown below.

Calculated losses and results due to the presence of combustible gases in the flue gases in the three cases (steam pressure taken to be 80 pounds gage).

	Case 1.	Case 2.	Case 3.
Loss due to			
CO	227	313	572
CH_4	529	487	710
H_2	116	160	176
C_2H_4	280	387	564
Total loss	1,152	1,347	2,022
Calculated results:			
Heat value of 1 pound of "combustible" B. t. u.	14,660	14,660	14,660
Heat evolved in furnace do	13,460	13,270	12,670
Dry gas per pound of "combustible" pounds	14.23	19.3	27.71
Water vapor per pound of "combustible" do	0.5887	0.5887	0.5887
Temperature of product of combustion (if completeness of combustion were 100 per cent) °Fa	2,075	2,906	3,850
Probable completeness of combustion per cent	91.8	90.5	86.4
Probable temperature of products of combustion °F	1,903	2,624	3,310
Probable flue-gas temperature do	543	598	639
Heat absorbed by boiler B. t. u.	9,424	10,053	9,875
Boiler efficiency	69.9	75.9	77.8
Over-all efficiency	64.2	68.7	67.3

[a] Specific heats assumed to be constant.

The diagrams giving the representation of the various quantities of heat of the three cases discussed are presented in fig. 55. Each of the areas ABCD is the potential heat in the coal; the areas BCFE are the incomplete combustion losses; each of the areas AEFD is the heat actually evolved in the furnace. Of the heat evolved in the furnace only the area GEFH in each diagram is the heat absorbed by the boiler. The minor losses are not represented in detail.

The over-all efficiency indicates that it is better to burn the coal with the initial temperature given in case II than with the high initial temperature given in case III, although the latter gives much better results than the low temperature in case I. On account of the increased radiation at high temperature, the actual results in case III might not show so much advantage over case I as the calculated results.

Another disadvantage of high initial temperature is the deterioration of the furnace. When high furnace temperatures are used the bridge wall has to be rebuilt often and the side walls lined. A hot fuel bed melts the refuse on the grate and causes the formation of clinkers. Hot clinker warps and destroys the grate bars, besides

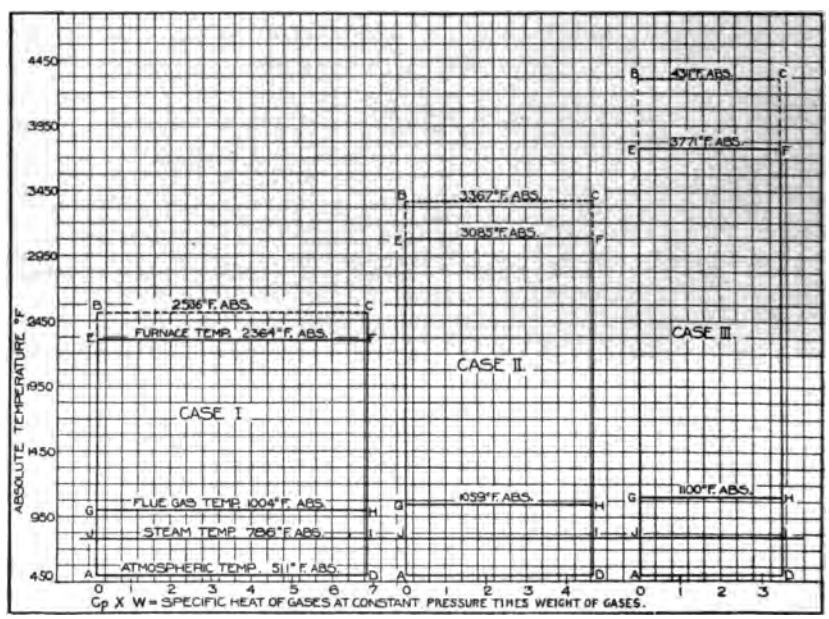

FIG. 55.—Availability to a boiler of heat of combustion of carbon in three different cases.

making the fires very hard to clean and disturbing the evenness of the air supply through the fuel bed.

Fig. 17 shows that in general the capacity of the boiler increases as the combustion-chamber or initial temperature rises. The advantages and disadvantages of high initial temperature may be summarized as follows: Advantages—(*a*) Increase in boiler efficiency; (*b*) increase in capacity. Disadvantages—(*a*) More loss by incomplete combustion; (*b*) increased radiation; (*c*) deterioration of furnace.

LOW STEAM PRESSURE AND ITS EFFECT ON ECONOMY.

It has been said that more heat could be made available and more heat would be absorbed by the boiler if lower steam pressure were used. For power purposes, however, the gain in boiler efficiency

would be more than offset by the loss in availability of the heat for the engine. If, however, the steam at low pressure be highly superheated and used in a steam turbine specially designed, an increase of 1 to 4 per cent in the thermodynamic efficiency of the outfit might be expected.

In the following paragraph is a conservative computation of the probable increase of the efficiencies of a boiler and a steam turbine resulting from the reduction of steam pressure and the superheating of the steam. In the computation of the steam-turbine efficiencies it has been assumed that the friction of the steam through the nozzles and the turbine blades would decrease as the pressure dropped, and that the expansion of the steam would therefore be more nearly adiabatic. This reduction of friction can be reasonably expected, because the friction of fluids against a solid increases directly as the density of the fluid. Furthermore, the expansion of highly superheated steam at low pressure will take place entirely in the superheated region, and thus friction due to condensed steam, which is a serious item in steam turbines as ordinarily built and operated, will be avoided.

Let four cases be considered—case 4, gage pressure 200 pounds, superheat 200° to 587.5° F.; case 3, gage pressure 100 pounds, superheat to 800° F.; case 2, gage pressure 25 pounds, superheat to 800° F.; case 1, gage pressure 15 pounds, superheat to 800° F.; temperature of feed water, 82° F.; condenser vacuum, 1.2 pounds absolute pressure (28 inches mercury below an atmospheric pressure of 14.7 pounds). Assume the coal of test 204 to be burned with the resulting product of combustion equal to 19.3 pounds of dry chimney gases per pound of "combustible." The heat in chimney gases per 1° F. per pound of combustible is, in dry gases, $19.3 \times 0.24 = 4.63$ B. t. u.; in moisture, $0.5887 \times 0.48 = 0.28$ B. t. u.; total, 4.91 B. t. u. The heating value of 1 pound of combustible is 14,660 B. t. u. About 83 per cent of the increase in the heat available for the boiler due to the drop of steam temperature will be absorbed (the true boiler efficiency being taken at about 83 per cent).

Calculated increase of boiler efficiency due to drop in steam temperature.

	Drop of steam pressure (pounds) from 200 to —		
	100.	25.	15.
Heat taken out of flue gases due to drop of steam temperature B. t. u.	244	491	564
Probable increase in boiler efficiency, per cent	1.66	3.35	3.85

This increase in boiler efficiency may seem small. However, the great reduction of the first cost of installation of a plant makes the reduction in steam pressure appear more practicable—for instance,

multitubular boilers would then be as safe as water-tube boilers. Further, 83 per cent true boiler efficiency should be far surpassed in the future.

Quantities used in calculation and probable results of the use of steam of low pressure and high superheat in steam turbines.

	Case 1.	Case 2.	Case 3.	Case 4.
Steam pressure by gage.....pounds..	15	25	100	200
Steam pressure, absolute.....do..	29.7	39.7	114.7	214.7
Temperature of saturated steam.....°F..	249.5	267.0	327.0	387.5
Temperature of superheated steam.....do..	800	800	800	587.5
Temperature of superheated steam, absolute.....do..	1,260.8	1,260.8	1260.8	1,048.3
Total heat of superheated steam above 82 °F. (λ_1)...B. t. u..	1,372.5	1,369.0	1357.0	1,245.0
Total heat in steam at 28-inch vacuum above 82 °F. (λ_2)..do..	1,035	1,031	978	888
$\lambda_1-\lambda_2$.....do..	337.5	338	379	357
Assumed coefficient of friction of steam in nozzle and blades (see p. 103).....	0.10	0.12	0.24	0.30
Coefficient of friction calculated from the law of friction of fluids, assuming the one in case 4 to be 0.3.....	0.084	0.10	0.22	.....
Heat converted into work, H_w, calculated with the assumed coefficient of friction.....	303.0	297.5	288.0	250.0
Thermodynamic efficiency of steam turbine.....	22.1	21.7	21.2	20.1
Over-all efficiency of steam-generating outfit.....	68.85	68.35	66.66	65.0
Combined thermodynamic efficiency of boiler and turbine....	15.2	14.8	14.1	13.1
Gain in combined thermodynamic efficiency of boiler and turbine over case 4.....	16.1	13.0	7.6	.....

The coefficient of friction of steam in nozzles and blades was assumed to be 0.3 for case 4, which is in close agreement with practice. The coefficients of friction for the other three cases were taken somewhat larger than those calculated from the law of friction of fluids, in order to be safe.

The over-all efficiency of a steam-generating outfit in case 4 was assumed to be 65.0, which can be attained in a well-operated boiler room. The over-all boiler efficiencies in the other three cases were obtained by adding to 65 the increase in efficiency as calculated in the preceding paragraphs.

Fig. 56 shows the cycle of thermodynamic processes of each of the four cases. In the chart the subscripts 1, 2, 3, and 4 of the letters refer to cases 1, 2, 3, and 4, respectively; letters having no subscripts are applicable to all cases.

Take case 4 for example: The area under AB_4 represents the sensible heat of the water, the area under B_4C_4 the latent heat of steam, and the area under C_4D_4 the heat in the steam due to superheat at constant pressure; the total heat in the superheated steam as it reaches the steam turbine is then represented by the area under $AB_4C_4D_4$. If there were no friction of steam during the expansion in the steam nozzle and the blades the expansion would be purely adiabatic, and in the diagram it would be represented by a vertical line from the point D_4. However, since friction comes into play during the expansion and changes part of the velocity of steam back into heat, the expansion is a combination of the processes of adiabatic expansion and heating at constant pressure, and is represented

in the chart by the curve D_4F_4. The heat rejected to the condenser is the heat under AEF_4. In cases 1 and 2 the heat rejected is the heat under $AEHF_1$ and $AEHF_2$, respectively, since the steam reaches the condenser in a slightly superheated state. The difference between the heat delivered to the turbine and the heat rejected to the condenser is the heat which has been transformed into the velocity of steam which is represented by the area under $AB_4C_4D_4$ minus the area under AEF_4. It must be understood that the heat changed into motion is not represented by the area inclosed by $EB_4C_4D_4F_4$.

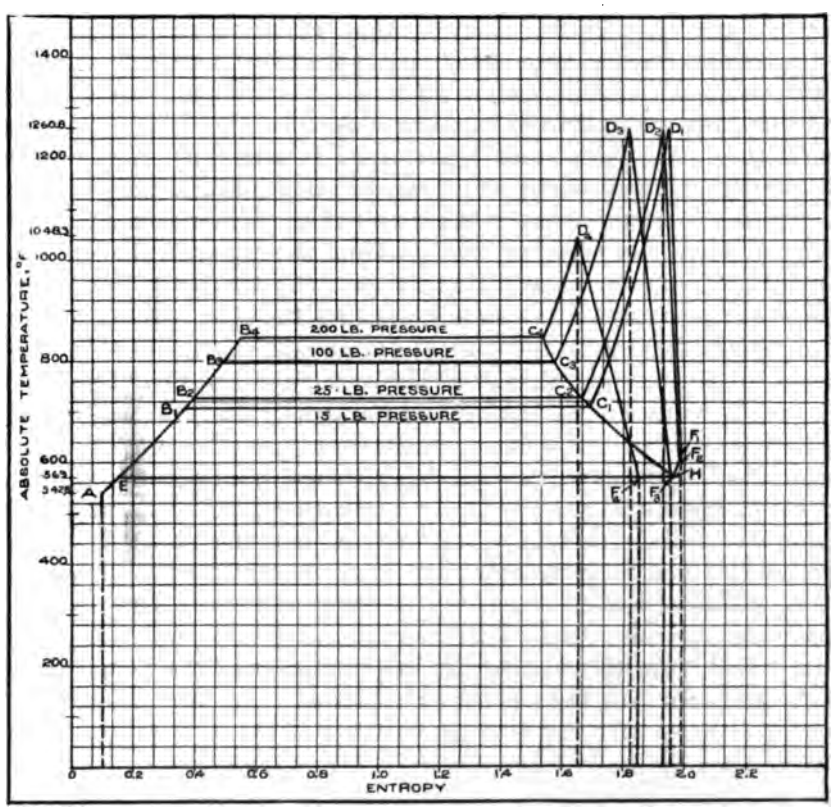

FIG. 56.—Temperature-entropy diagrams for steam-turbine cycles.

HEAT TRANSMISSION THROUGH BOILER TUBES, AND TRUE BOILER AND FURNACE EFFICIENCIES.

From the very start of the steaming tests those conducting them sought to separate the performance of the boiler as a heat absorber from the performance of the fuel bed and furnace as a heat producer. In writing up the stages through which opinions progressed it seems best to adopt the historical method and outline all attempts, up to the last calculations, which are both theoretical and practical, being determined from about 400 tests. This last work must be taken as

neither final nor even necessarily correct; it is simply the best we know at present. All opinions expressed or deductions drawn must be understood as merely tentative, and the right is reserved to change part or all of them at any future time.

The first definite calculations on boiler efficiency were made in January, 1906, in an attempt to check the temperature indications of a Wanner optical pyrometer, which had been used to ascertain the temperatures in the rear of the combustion chamber. Sometimes the observation was taken by looking at flame, in which case it was postulated that the flames of various coals differ in brightness at the same temperature; and, perhaps, although the particles of incandescent carbon from which the pyrometer received its light were really at the temperature as read off the scale, such a likely condition was no assurance that the molecules of gas between were as hot; the reasonable assumption would be that they were cooler. Or, worse yet, when a coal and the conditions of a test were such as to give short flames, or none, in the rear of the combustion chamber, and the pyrometer received its light from the opposite side wall, it was plainly evident on observation that the temperature as read from the instrument was too low, because the side wall was cooler than the tile furnace roof, on account of its radiating heat to the bare water tubes near by, which the tile roof could not do. Even the tiles of the roof were conducting heat through to the tubes which they protected. These and other considerations put the indications of the optical pyrometer in question, through no fault of its own. Attempts were made to check the pyrometer with a platinum and platinum-rhodium thermoelectric couple, but the porcelain tubes slagged and melted away within an hour or so under the high temperatures used, and a satisfactory protection for the junction was not made to work reliably until too late for this purpose. By this time it had been learned that the ascertainment of the temperature of the gases entering the boiler was not, after all, of such overwhelming importance. So this tedious checking of the optical pyrometer was dropped for more fruitful work. There is a general impression among the observers that the pyrometer when used on such furnaces as these is usually correct within 50° C. or 100° F. (For a description of the method of protecting the thermoelectric couple with a water jacket and cheap clay pipestems see p. 54.)

These calculations on boiler efficiency were made because an attempt to obtain any curve of relationship between combustion-chamber temperatures (obtained by the Wanner optical pyrometer) and over-all efficiency of the furnace and boiler combined resulted in a failure, the points falling all over the sheet of coordinate paper. At that time the impression of the staff was that the following formula

applied to boilers as well as to condensers, and so it does, but that is only one-third of the story:

Efficiency of boiler as a heat absorber $= \frac{t_1 - t_2}{t_1}$ where t_1 = initial temperature of gases above atmosphere, and t_2 = final temperature of gases above atmosphere.

Many of the staff believed at that time that if the air supply per pound of coal were reduced, without decreasing the completeness of combustion (in consequence of which the initial temperature t_1 would rise), the final temperature t_2 would fall, or at least not rise proportionately with t_1. It is frequently stated by authorities on boiler testing that if the same number of heat units be liberated in a furnace per second in two cases—first, with a small air excess, and second, with a large air excess—the final or flue temperature in the first case will be the lower. This assumption may be true with some boilers, or with most boilers, or even with those of this plant, but after careful investigation of large numbers of actual simultaneous readings, the staff has become convinced that such a theory is both practically and theoretically untrue; and that, on the contrary, a rise of furnace temperature usually causes a proportionate rise of flue temperature, the ratio between these temperatures being almost independent of the mass of gases passing. For a long time this conclusion was hard to believe, for on closing the stack damper a little, at times, the combustion-chamber temperature rose and the stack temperature fell; yet nothing appears more certain on observation than that the sun moves around the earth.

It seemed almost axiomatic that the higher the initial temperature the greater the amount of heat which would pass into the boiler because of the greater temperature difference between gases and water, yet this proposition is only slightly true. Likewise it seemed axiomatic that a high combustion temperature would certainly aid combustion of smoke and hydrocarbons, which it would do if other accompanying conditions were not usually adverse enough to neutralize all gain. Because of these two propositions, which were apparently axiomatic, it was concluded that when the optical-pyrometer temperatures and the over-all efficiencies of the fuel bed, furnace, and boiler (72*) failed to agree, the pyrometer was given unreliable indications, through no fault of its own. So the first calculation was incidentally made of what was then called true boiler efficiency, in order to figure backward to the combustion-chamber temperatures, by means of the above formula, $\frac{t_1 - t_2}{t_1}$. The so-called true boiler efficiency was calculated for each of about 125 tests by means of the formula.

True boiler efficiency =

$$\frac{\text{Efficiency 72*}}{100 - [\text{CO loss in p. ct.} + (\text{unaccounted-for item in p. ct.} - 3 \text{ p. ct.})]}$$

All the above percentages were taken from the tests as calculated by the A. S. M. E. code. It will be noticed that the incomplete-combustion loss was taken as being the unaccounted-for item minus 3 per cent radiation. This was very crude, but the best we knew. The results were disappointing and not clear, but as negative results they were very instructive. Eighty-eight per cent of the so-called true boiler efficiencies fell between 70 and 75 per cent, and such uniformity surprised everyone. The combustion-chamber temperatures, calculated backward by equating these efficiencies to the expression $\frac{t_1 - t_2}{t_1}$ in which t_2 was known, turned out ridiculously low and the individual temperatures were very erratic. On leaving out a few abnormal tests, more than 90 per cent of those remaining had a so-called "true boiler efficiency" between 70 and 75 per cent. These calculations took much hard work, the details of which are omitted, inasmuch as it gave only negative and prophetic results that were of little value in themselves.

The great value of the work lay in the result that it shook previously conceived ideas, some of which were widely believed. The consequent inquiry took two forms—(*a*) a general mathematical study of the impartation of heat from fluids (including gases) to solids and vice versa,[a] and (*b*) a routine analysis of samples of gases from the rear of the combustion chamber and the stack for minute traces of hydrogen and hydrocarbons.

An ordinary Hemple pipette and absorption bulbs for analysis of illuminating gas are accurate only to about 0.2 or 0.3 per cent when very carefully manipulated. Unfortunately a mere trace of methane—for instance, to the extent of 0.1 per cent by volume in the flue gases—is sufficient to represent ordinarily a loss of 2 per cent of the coal due to incomplete combustion. (See p. 100.) Nevertheless, for some weeks several analyses were made daily for traces of hydrogen and hydrocarbons, and on several days these constituents occurred persistently and very appreciably, so as to indicate losses of many per cent due to incomplete combustion. On account of the well-known difficulty of obtaining accuracy in determinations of this kind, due to the small volumes of these gases that are ordinarily present, this work will not be published. It has, however, along with many kinds of circumstantial evidence, strengthened the belief that the losses due to incomplete combustion generally amount to several per cent of the potential heat in the coal burned. This presumptive loss will also be investigated in one or two other ways.

Incidentally it may be remarked that, if developed, such methods of measuring minute traces of hydrogen and hydrocarbons will be

[a] It was fortunately found that John Perry had done much excellent, but mathematically involved, work on this subject; an account of it is given in his book "Steam Engines and Gas and Oil Engines."

useful when applied to gas-engine exhaust gases. The mere analysis of exhaust gases for CO_2, O_2, and CO, resulting in no trace of CO, does not prove complete combustion by any means.

THEORETICAL CONSIDERATIONS.

The tentative formulas developed by Perry are so significant and so important that a general outline of them is here given. According to his theory the rate of heat impartation to a boiler tube is, for ordinary gases, proportional to (1) temperature differences of the gases and the metallic surface; (2) density of the gas; (3) velocity of the gas parallel to the metallic surface, and (4) specific heat of the gases at constant pressure. The first of these factors is the only one usually thought of, and its applicability is perhaps self-evident.

In considering factor 2 it is plain that the individual molecules of gas give up their heat by vibrating against the metal. The greater the number of molecular impacts per second against a unit area of the tube the greater the amount of vibration (heat) imparted to the molecules of the metal. But the number of impacts is directly proportional to the density, or weight per liter or cubic foot. At a constant pressure (a little less than atmospheric in boiler practice), the density is inversely proportional to the absolute temperature, and at high-furnace temperature it is almost inversely proportional even to the temperature reckoned above steam temperature. On this account there is a direct neutralization of gain when striving for high temperature in steam-boiler practice, for as the temperature is raised the number of molecules in action against any portion of the heating surface is reduced.

In considering factor 3 a mental image should be formed of the appearance of a cross section of intensely magnified heating surface. The molecules of the metal would probably appear to be in an extremely rapid state of vibration, with spaces between them much larger than the molecules. Entangled among the outer molecules there would be comparatively stationary molecules of gas held close together in a dense film next to the metal. Farther out normal gas is reached, where the molecules are widely scattered. All these gaseous molecules, from those entangled among the surface molecules of metal to those in the gas of normal density, would be in an invisibly rapid state of vibration, but those close to the metal would be more or less "bound" by the attraction of the metal. Now, this layer of condensed gas, so to speak, is very adherent to the metal, and consequently a very poor conductor of heat (since heat in material bodies is a matter of the vibration of their molecules), so that the hope of getting heat through it lies in the possibility of dislodging slowly vibrating (cold) molecules from this layer and replacing them with rapidly vibrating (hot) ones. It can be imagined that as a stream

of hot gas moves along the metal parallel to its surface, an average of one-third of its molecules are flying back and forth perpendicular to the surface, and the dislodging, sweeping, or scrubbing effect of these molecules on the layer of gas molecules adhering to the metal is proportional to the velocity of the mass of gas parallel to the heating surface. Thus it is that the velocity of gases through a boiler tube (a fire tube, for instance) is an important factor in heat absorption. It is this dislodgment that makes a boiler respond in amount of steam made to any reasonable demands put on it. If twice the mass of gas is put through the tube per second at the same initial temperature, very nearly twice as much steam will be generated on the other side of the tube.

In considering factor 4, the specific heat of the gas at constant pressure, it is evident that inasmuch as a cubic centimeter of any gas at any temperature and pressure contains the same number of molecules as a cubic centimeter of any other gas under the same conditions (Avogadro's law), and inasmuch as various gases on cooling give up various amounts of heat per degree of temperature drop—that is, they have different specific heats at constant pressure—a given number of molecular impacts of different gases will give up more or less energy, according as the specific heats of the gases are respectively more or less.

The relation between the heat transmitted per second per unit of heating surface and the four factors is expressed by the equation—

$$H = Cpv\ (T_1 - T_s)$$

where H = the amount of heat transmitted;
C = the specific heat times a constant;
p = density of the gas;
v = velocity of the gas parallel to the metallic surface;
$(T_1 - T_s)$ = the difference of temperatures of the gases and the water.

Perry[a] arrives at the above equation by the following reasoning: Referring to fig. 57, let AB represent a small portion of a heating surface. G_1 to G_4 are molecules of the gas that are entangled among the molecules of the metal and therefore have no velocity parallel to the surface of the boiler plate; however, these molecules have velocity of vibration in all planes due to their temperatures. M and M_1 are molecules of the gas which have not only the velocity of vibration, but also the velocity parallel to the heating surface. Inasmuch as the conductivity of the metal itself in a boiler flue is so great that there is very little difference of temperature between the gas surface and

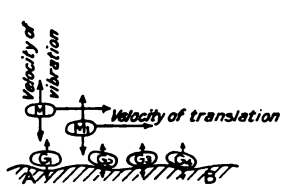

FIG. 57.—Diagram illustrating the theory of the dislodgment of adhering gaseous molecules from the surface of a metal plate.

[a] Steam Engines and Gas and Oil Engines, pp. 587-591.

the water surface, the heat transmitted through the metal may be taken to be equal to the heat imparted to the film of the gas adhering to the metal. This assumption makes the temperature of the film equal to the temperature of the metal and also to that of the water. Now, suppose n represents the number of the molecules (M) which enter the adhering film of the gas, and also the number of molecules (G) which leave the film of the elementary surface AB per unit of gas. Let T_1 be the average temperature of the entering molecules, and T_s the temperature of the film and of the leaving molecules. The molecules enter and leave the film with an average momentum in the axial direction that is proportional to the axial velocity (v) of the gases through the flue. The force of friction (F) is the axially directed momentum given to the adhering layer of molecules, so that per unit area the friction (F) is proportional to nv (as the momentum of a body is the product of its weight and its velocity). The heat (H) given to the film per second per unit surface AB is proportional to $n\ (T_1 - T_s)$, or—

(1) $H = Cn\ (T_1 - T_s)$, where C is a constant.

(2) But as $F = Cnv$,

(3) Then $H = K \dfrac{F\ (T_1 - T_s)}{v}$, where K is another constant.

Now, the friction of fluids against a solid varies directly as the density and the square of the velocity of the fluid, or—

(4) $F = Cpv^2$, where p is the density of the fluid.

By substituting for F in equation 3 its value in equation 4, the fundamental equation as given before is obtained:

(5) $H = Cpv\ (T_1 - T_s)$.

In the foregoing equations the C and K are constants employed so that the sign of equality could be used.

Equation 5 gives the amount of heat transmitted per second per elementary area of heating surface. If the amounts of heat transmitted by every elementary area are added, the heat transmitted by the entire heating surface per second can be obtained. This can be done by the use of calculus, as follows:

Take $T_1 - T_s = \Theta$; T_1 being the absolute temperature of the gases at the distance x from the furnace end of a flue of a total length l and diameter D, and T_s being the temperature of the steam. Let W pounds of gases flow through the flue per second and let the specific heat be a constant:

$$p = \frac{C}{v}, \text{ and } v = C''T$$

where C and C′ are temporary constants.

(6) Then $p = \dfrac{C''}{T}$, where C″ is a consolidation of C and C′ just above.

Also volume per second $= \dfrac{W}{p} = \dfrac{\pi D^2 v}{4}$, where D is the diameter of the fire tube and $\pi = 3.1416$.

(7) Whence $v = \frac{KW}{pD^2} = \frac{K'WT}{D^2}$, where K and K′ are constants.

Equations 6 and 7 are derived also from the laws that (1) the density of the gases varies inversely as the absolute temperature and (2) the velocity varies directly as the weight of the gas that passes through the flue in a second and as the absolute temperature, and inversely as the square of the diameter of the flue. By substituting the values of p and v from equations 6 and 7, equation 5 becomes—

$$H = \frac{Cv\Theta}{T} = -\frac{C'W\Theta}{D^2}.$$

Hence in a short length (dx) of the boiler flue the heat transmitted to the boiler is—

$$-C_pWd\Theta = \frac{C'W\Theta}{D^2} \times D\pi dx = \frac{CW\Theta dx}{D}$$

But $\int \frac{d\Theta}{\Theta} = -\int \frac{Cdx}{D}$. Integrating, $\log_e\Theta = -\frac{Cx}{D} + K$.

When $x = 0$, $K = \log_e\Theta_0$. When $x = l$, $\log_e\Theta_l = -\frac{Cl}{D} + \log_e\Theta_0$ and $\frac{\Theta_l}{\Theta_0} = e^{-\frac{Cl}{D}}$.

(8) $\therefore \Theta_l = \Theta_0 e^{-\frac{Cl}{D}}$.

The heat absorbed by the whole flue of the boiler per second is—

(9) $H = C_pW\left(\Theta_0 - \Theta_0 e^{-\frac{Cl}{D}}\right) = C_pW\Theta_0\left(1 - e^{-\frac{Cl}{D}}\right)$;

and the true efficiency of the flue is—

(10) $E = \frac{C_pW\Theta_0\left(1 - e^{-\frac{Cl}{D}}\right)}{C_pW\Theta_0} = 1 - e^{-\frac{Cl}{D}}$.

TRUE BOILER EFFICIENCIES DEPENDENT ONLY ON PHYSICAL SIZE, SHAPE, AND ARRANGEMENT OF BOILER.

Equation 10 states that the true efficiency of the boiler flue depends only on its length and diameter and not on the initial temperature of the gases. What is true about one flue holds good for all together.

The efficiency expressed by equation 10 is the true boiler-flue efficiency—that is, it is the ratio of the heat absorbed by the boiler flue to the heat available for absorption.

It must be remembered that in this discussion only the heat that is imparted to the boiler flue by convection and conduction has been considered. In reality the boilers receive heat also by radiation directly from the fire and from the hot walls of the furnace. According to the law of Stefan and Boltzmann the amount of energy radiated by a black-body surface to another body is proportional to the difference of the fourth powers of their absolute temperatures. The boiler furnace radiating heat to the boiler is nearly a black-body surface, so

that the heat received by the boiler by radiation may be expressed by the equation—

$$H = C\ (T_1^4 - T_s^4)$$

where T_1 is the absolute temperature of the furnace, T_s the absolute temperature of the boiler tubes, and C a constant.

INFLUENCE OF VELOCITY OF GASES ON HEAT ABSORPTION.

The influence of the velocity of gases on the heat absorption may appear at first somewhat improbable. However, inasmuch as high capacities of all types of boilers are obtained simply by burning more coal, which means making more hot gases and passing them over the heating surface at a higher velocity, it must be admitted that such an influence exists. Thus, for example, in locomotive practice the capacity is increased two or three times by doubling or tripling the rate of combustion and therefore doubling or tripling the velocity through the boiler flues. Of course the rate of heat absorption by the fire box is affected principally by the initial temperature.

In fig. 6 (p. 15) the following three factors in heat absorption are shown, with their product, for the gas mixtures resulting when 1 pound of carbon is burned with various amounts of excess air: (1) Temperature difference, (2) density of gases; (3) volume of gases, which is proportional to velocity parallel to the heating surfaces.

The specific heats of products of combustion with the various air excesses are nearly constant at 0.24, and therefore any errors introduced by neglecting to consider such varying compositions would be less than about 1 per cent. In the case of some wet lignites the error might be more, because of the presence of considerable percentages of water vapor with a specific heat of 0.48 or higher. The temperatures of combustion were calculated on the assumptions that complete combustion is possible, and that the specific heats of oxygen, nitrogen, and carbon dioxide remain constant, which is not likely. Any error thus introduced into the calculated temperature is neutralized by an opposite and very nearly proportionate secondary error, introduced into the calculated density as a consequence of the primary error. On account of these compensating errors the uppermost "products" curve is as reliable as the whole theory.

The assumption was made that 1 pound of carbon was always burned in the same length of time, with various air excesses, and the resulting temperatures were calculated in degrees Fahrenheit. On the same data the relative densities of the resulting gaseous mixtures were calculated, each at its respective temperature, taking as unit density that of the gases at 320° F. (the temperature of the boiler water in this plant).

The lower curve, relative volume of products of combustion with increasing air supply, indicates that with large air excesses—that is,

with low furnace temperatures—the actual volumes are comparatively high, but within the reasonable working range of even poor and good firing the volume of the products is nearly constant; as the air excess is reduced the temperature rises almost as fast and the effect on the resulting total volume is to decrease it very slightly.

Relative volume was used because the velocity of passage of the gases through the boiler is directly proportional to it, other things being equal, and, as already stated, velocity is one of the three most important factors determining the amount of heat imparted to the metal of the boiler tube.

It is assumed that in each case the products of combustion, generated always in the same length of time, are passed through a boiler fire tube. The upper ("products") curve gives by its ordinate the amount of heat absorbed by the first small portion of the tube during that length of time. On page 110 it is shown that this curve represents not only the amount of heat absorbed by the first short length of a tube but by the whole tube, so that this curve can be applied to the whole heat absorption of a boiler so far as absorption by convection is concerned; but it can not be applied to heat absorption due to radiation from fuel bed or hot brickwork.

The upper and final curve was obtained by multiplying together, for each of several temperatures along the whole range, the three factors (1) relative density of gases, (2) temperature of gases minus temperature of steam ($T_1 - T_s$), (3) relative volume. The curve starts at zero heat absorption, because, although the density and volume are high, the temperature difference at 320° F. is zero, consequently the product of the three is zero. The ordinate figures at the left have no specific names, but merely furnish a scale on which to indicate relative magnitudes of volume, density, and products of these two, and temperature excess above that of boiler water. As applied to the upper curve these ordinates on the vertical scale do not mean B. t. u., though they are proportional to actual numbers of B. t. u. absorbed in any specific case.

On inspecting the upper curve the striking fact is its rapid approach to the horizontal, beginning at comparatively low furnace temperatures. For instance, at a furnace temperature of 2,000° F. (1,100° C.)—ordinary temperature scale; see second temperature scale at foot of chart—a temperature very easy to attain even with poor coals, the ordinate at the left is 9.0. At a furnace temperature of 3,000° F. (1,650° C.)—second temperature scale at bottom of chart—a temperature rather hard to attain and destructive to good fire bricks, the ordinate at the left is 9.5, only 5.5 per cent more than 9.0. Thus for all the extra trouble and expense of attaining the higher furnace temperature there is a gain in the efficiency of the boiler as a *heat* absorber of only 5.5 per cent, reckoning the efficiency calcula-

tion above atmospheric temperature. This gain is often largely neutralized by less complete combustion. The fact that the efficiency 72* is not improved by high combustion-chamber temperature is well illustrated in fig. 12 (p. 21), which is compiled from actual tests on coals of the same class from Illinois and Indiana.

It must be understood that this whole chart refers only to that part of a boiler which absorbs heat by contact with the hot gases. In a locomotive boiler this includes the tubes and to some extent the fire box. For a water-tube boiler of the Heine type, with the lower row of tubes inclosed in clay tiles, the chart includes all of the boiler except the lower row of tubes, which are exposed in the rear to radiation and are analogous to the fire box of a locomotive.

The following table gives a laborious method of calculating the relative amount of heat absorbed by the boiler when 1 pound of carbon is burned with various amounts of excess air. The table was calculated by first figuring the relative volume, the relative density, and the temperature elevation of the gases; then by multiplying these three together the relative heat absorption was obtained for the corresponding excesses of air. The curves of fig. 6 (p. 15) were plotted from the values given in this table:

Arithmetical calculation of relative amounts of heat absorbed by a hypothetical boiler.

	1.	2.	3.	4.	5.	6.	7.	8.	9.
Excess of air.....per cent..	0	25	50	75	100	150	200	300	1,595
1. Pounds of O_2 per pound of carbon.....	2.67	3.33	4.00	4.67	5.33	6.67	8.00	10.67	45.20
2. Pounds of air per pound of carbon (4 parts N, 1 part O).....	13.33	16.67	20.00	23.33	26.67	33.33	40.00	53.33	226.00
3. C_p of products of combustion.....	0.2360	0.2370	0.2373	0.2375	0.2376	0.2378	0.2380	0.2385	0.2390
4. Temperature rise due to combustion= $\frac{14,600}{C_p\text{(pounds of air}+1)}$ ...°F..	4,325	3,486	2,930	2,526	2,220	1,788	1,496	1,127	270
5. Temperature rise + 50 (which is atmospheric temperature)..... °F..	4,375	3,536	2,980	2,576	2,270	1,738	1,546	1,177	320
6. Absolute temperature of combustion..... °F..	4,836	3,997	3,441	3,037	2,731	2,299	2,007	1,638	781
7. Relative volume of unit mass of gases at temperature of line 6 when volume at 461° F. absolute=1.....	10.49	8.67	7.47	6.59	5.92	4.98	4.35	3.55	1.69
8. Relative total volumes of products of combustion, each at its final temperature of combustion=line 7×line 2..	1,139.8	144.5	149.4	153.5	157.88	165.9	174.0	189.3	382.0
Elevation of temperature of combustion above steam temperature:									
9. At 320° F., 75 pounds on gage .....°F..	4,055	3,216	2,660	2,256	1,950	1,518	1,226	857	0
10. At 390° F., 205 pounds on gage .....°F..	3,985	3,146	2,590	2,186	1,880	1,448	1,156	787	0
11. Density of products of combustion, each at its final temperature of combustion when density at 320° F.=1.....	0.1615	0.1956	0.2269	0.2568	0.2856	0.3397	0.3891	0.4768	1.000
12. Line 11×line 9×line 8=Ha.....	916	909	902	889	879	855	830	774	0

[a] This H is merely a number proportional to the heat absorbed.

The relative amount of heat absorbed by a boiler when various percentages of excess of air are used for combustion can be easily obtained by the following formula:

$$(11)\quad H = CW\left(\frac{60{,}900 - KW}{W - 1}\right)$$

which is obtained as follows:

Let C = a constant, having a fixed value for each case.

p = the density of the gases, relative to any standard.

V = velocity past any small portion of heating surface under consideration, in any units.

T = absolute temperature of gases at any point under consideration, on any thermometric scale.

t = absolute temperature of boiler water on the same scale as T.

W = weight of gases resulting from combustion of 1 pound of carbon, expressed in any units of any system.

W − 1 = weight of air used per pound of carbon.

K = −Ta (temperature of atmosphere) + t.

According to our fundamental assumption (equation 5, p. 111), the heat transmitted per second per unit of heating surface is—

$$(5)\quad H = CpV\ (T - t).$$

But $p = \frac{C'}{T}\left(\frac{W}{W-1}\right)$, where C′ is a new temporary constant. Also $V = C''\ TW$, where C″ is a new temporary constant.

The last two equations are derived from the fundamental properties of gases; the first one states that when 1 pound of carbon is burned with air the density of the resulting gases approaches that of air as the amount of air increases, which increase reduces the influence of the amount of CO_2 present; and the second, that the density decreases directly as the absolute temperature (T) of the resulting mixture increases. C′ is some constant, whose value will not be determined because all these results are relative only. This statement applies to all the C's used. Substituting the values of p and V in equation 5, we have—

$$H = C\left(\frac{W}{W-1}\right) \times \frac{C'}{T} \times C''\ TW\ (T - t) = \frac{CW^2}{W-1}(T - t)$$

on arbitrarily assuming that all constants, C, C′, and C″, are consolidated into a new C, as the result sought is to be relative only.

$$T - Ta = \frac{14{,}600}{0.24\ W} = \frac{60{,}900}{W}$$

hence

$$T = \frac{60{,}900}{W} + Ta$$

in which 14,600 = B. t. u. value of 1 pound of carbon and 0.24 =

specific heat (approximately) of 1 pound of the gases of combustion at constant pressure. Substituting again, we have—

$$H = \frac{CW}{W-1}\left(\frac{60,900}{W} + Ta - t\right)W = CW\left(\frac{60,900 - KW}{W-1}\right)$$

which is the equation given first above.

It was suspected that these calculations of heat imparted to the boiler surface might be slightly vitiated by the fact that CO_2, O_2, and N_2 have different specific heats. A trial calculation with two very different air supplies showed that this error could not be more than 1 per cent in favor of greater heat absorption with a low air supply.

The curves of fig. 20 (p. 29) were plotted from data obtained by formulas developed in the preceding paragraphs. This chart shows the same facts as fig. 6 (p. 15), but they are differently represented. The two charts were calculated at different times by different men, who used slightly different constants in some ways. One of them took account of the slight variation of composite specific heats of the gases with different air excesses and the other did not. Nevertheless, the two charts show graphically the same conclusion—that at low air excesses and high initial temperatures the heat absorption by the boiler increases only a few per cent as compared with moderate furnace temperatures. If we use the same temperature range as in the discussion of the curves of fig. 6 (p. 15)—2,000° F. (1,100° C.) to 3,000° F. (1,650° C.)—the amount of heat absorbed increases 7 per cent, as figured from the ordinate at the left. The increase calculated from the chart was 5.5 per cent.

The arrows attached to each curve indicate the coordinates to be used with it. The ordinate on the left, "Heat transmitted per second per unit of heating surface times a constant," is relative only, as indicated by the phrase "times a constant." This constant varies with the boilers. Every boiler has an individual constant, and according to this theory it is unchangeable except by changes in baffling, when it becomes another boiler with a new individual constant.

The curve labeled "Combustion temperature as affected by air supply" was calculated as explained for the chart shown in fig. 6 using constant specific heats.

The curve labeled "Heat absorption as affected by combustion temperature" is precisely the same curve as the upper curve of fig. 6, with the exception of the calculation as explained above.

The curve labeled "Heat absorption as affected by air supply" shows the same fact as the upper curve with reference to air supply per pound of carbon instead of the resulting temperature of combustion.

With 14 pounds of air per pound of carbon the ordinate at the left is 6.2. With 28 pounds of air the ordinate is 5.55—a decrease of about 10.4 per cent. The latter amount of air is high in practice. To reduce the heat absorption to 50 per cent of what it would be if the carbon were completely burned with the theoretical amount of air (11.50 pounds) would require 108 pounds of air per pound of carbon—an enormous excess.

In all such calculations of heat absorption it is plain that the more nearly the temperature of the absorbing medium approaches that of the atmosphere—that is, the lower the steam pressure—the less the harm done by excessive amounts of air and the larger the percentage of total heat absorbed. This is an argument in favor of low steam pressures with high superheats, as suggested tentatively on pages 102–105.

PRACTICAL APPLICATION OF THEORY OF HEAT ABSORPTION TO A FIRE-TUBE BOILER.

As a practical illustration of the meaning of these theoretical principles, several calculations were made in the case of a fire-tube boiler assumed to consist of a single tube 0.1 foot in internal diameter and 10 feet long.

From the work of page 112 is taken the equation, which expresses the quantity of heat passing through any given portion of the tube.

$$(9)\quad H = CpW(\Theta_{x_1} - \Theta_{x_2}) = W\Theta_0\left(e^{-\frac{cx_1}{D}} - e^{-\frac{cx_2}{D}}\right)\times 0.24$$

in which H = heat absorbed in B. t. u.

Θ_0 = elevation of initial temperatures above boiler-water temperature.

Θ_{x_1} = elevation of temperature of gases above that of boiler water at a point x_1 feet from the entrance end of the tube.

Θ_{x_2} = elevation of temperature of gases above that of boiler water at a point x_2 feet from the entrance end of the tube (x_2 is farther along the tube than x_1).

W = pounds of gases per pound of carbon.

e = base of hyperbolic system of logarithms = 2.718.

D = internal diameter of tube in feet.

c = a constant for any particular tube.

0.24 = the approximate specific heat of gases of combustion at constant pressure. This factor might well have been omitted and its effect on the equation accomplished by giving the constant "c," in the exponents of e, another value.

The following calculations assume that the metal of the tube is always kept at the water temperature, which is not true, inasmuch

as there must be a difference of temperature in order to make the heat flow from the metal into the water. It must be understood at the outset that these calculations are not given for the purpose of proving anything, but merely to illustrate the concrete consequences of the theory. Other methods will be used and applied to actual boiler tests to show how closely the formula fits actual performances.

An ordinary locomotive boiler evaporates about 11.65 pounds of water (equivalent evaporation from and at 212° F.) per square foot of heating surface per hour. Our hypothetical boiler consists of one fire tube 10.0 feet long and of 0.1 foot internal diameter. Its heating surface is 3.1416 square feet and every second $\frac{11.65 \times 966}{60 \times 60} = 3.15$ B. t. u. are transmitted through each square foot.

Take the pounds of air per pound of carbon as 23.33, or 75 per cent excess above the theoretical, giving 24.33 pounds of gases of combustion per pound of carbon. The theoretical temperature of combustion is 2,576° F., assuming atmospheric temperature to be 50° F. In our case this is 2,576° − 320° = 2,256° F. above boiler water temperature. This 2,256° F. is our θ_0.

These calculations are to be for one second of time. It is more consistent with practice to assume that 1 pound of carbon is not burned in one second for 3.1416 square feet of heating surface, but in about 3,230 seconds.

Introducing this 3,230 as a correction factor in the above equation, and substituting all the above-calculated quantities, we get the following equation to be solved for "c," the physical or "size and shape" constant of this particular boiler:

$$3.1416 = 0.24 \times \frac{24.33}{3{,}230} \times 2{,}256 \times 2.718^{-\frac{c \times 0.0}{0.1}} - 2.718^{-\frac{c \times 10.0}{0.1}}$$

whence, on solving by logarithms, c = 0.0147.

Now let us take this hypothetical boiler of one fire tube and feed it with the gases resulting from the combustion of 1 pound of carbon completely burned (which is both theoretically and practically impossible with air supplies only a little above the theoretical), with increasing percentages of air excess. The factors are all grouped under case 1 of the table below; under case 2 are given parallel data for burning 2 pounds of carbon in the same time (3,230 seconds), and under case 3 for burning 10 pounds. The factors are repeated in the second and third cases to impress the fact that within reasonable limits the efficiency of a boiler proper as a heat absorber is independent of the capacity.

Calculations of the heat absorbed by a hypothetical boiler.

	Excess of air (per cent).	Case 1 (1 pound of carbon burned).			Case 2 (2 pounds of carbon burned).			Case 3 (10 pounds of carbon burned).		
		W.	θ_0.	H.	W.	θ_0.	H.	W.	θ_0.	H.
1	0	$\frac{14.33}{3,230}=0.00443\ldots$	4,055	3.3218	$\frac{(14.33)2}{3,230}=0.00886$	4,055	6.6436	$\frac{(14.33)10}{3,230}=0.0443$	4,055	33.218
2	25	$\frac{17.67}{3,230}=.00547\ldots$	3,216	3.2530	$\frac{(17.67)2}{3,230}=.01094$	3,21	6.5060	$\frac{(17.67)10}{3,230}=.0547$	3,216	32.530
3	50	$\frac{21.00}{3,230}=.00650\ldots$	2,660	3.1972	$\frac{(21.00)2}{3,230}=.01300$	2,660	6.3944	$\frac{(21.00)10}{3,230}=.0650$	2,660	31.972
4	75	$\frac{24.33}{3,230}=.00753\ldots$	2,256	3.1416	$\frac{(24.33)2}{3,230}=.01506$	2,256	6.2832	$\frac{(24.33)10}{3,230}=.0753$	2,256	31.416
5	100	$\frac{27.67}{3,230}=.00855\ldots$	1,950	3.0866	$\frac{(27.67)2}{3,230}=.01712$	1,950	6.1732	$\frac{(27.67)10}{3,230}=.0856$	1,950	30.866
6	150	$\frac{34.33}{3,230}=.010 3\ldots$	1,518	2.9839	$\frac{(34.33)2}{3,230}=.02126$	1,518	5.9678	$\frac{(34.33)10}{3,230}=.1063$	1,518	29.839
7	200	$\frac{41.00}{3,230}=.01269\ldots$	1,226	2.8769	$\frac{(41.00)2}{3,230}=.02538$	1,226	5.7538	$\frac{(41.00)10}{3,230}=.1269$	1,226	28.7 9
8	300	$\frac{54.33}{3,230}=.0.682\ldots$	857	2.6655	$\frac{(54.33)2}{3,230}=.03364$	857	5.3310	$\frac{(54.33)10}{3,230}=.1682$	857	2[illegible].655
9	1,596	$\frac{227}{3,230}=.07027\ldots$	0	0.0000	$\frac{(227)2}{3,230}=.14054$	0	0.0000	$\frac{(227)10}{3,230}=.7027$	0	00.000

If it be true that by raising the initial temperature of the gases entering a boiler by 1,000° F. the amount of heat put into the boiler for every pound of fuel is increased by only a few per cent, and if it also be true that the small amount of oxygen present in case of high temperatures tends to reduce the speed and consequently the completeness of combustion, how, then, does it happen that (as is undoubtedly a matter of common observation) a large air excess certainly lowers the over-all efficiency decidedly? The explanation probably is that when the air excess is large it is probably very large through the holes in the fire, and insufficient through the little hills and cakes of coal on the grate, especially if the latter are underlaid with clinker; the result is that along with a general large air excess there may be much incomplete combustion. It comes back to the old story that the fuel bed and combustion space are to blame. The remedy lies in a more even fuel bed and gas-mixing structures in the combustion chamber, rather than a low air excess or a thick fuel bed. With gas-mixing structures a stronger draft must be used if the capacity is to be kept up.

In confirmation of the above supposition, that the air excess may be insufficient through cakes of coal, reference may be had to page 59, where analyses are given of gases collected at the surface of the fuel bed through a water-jacketed sampling tube. Many samples contain large percentages of CO, hydrocarbons, and hydrogen, and no O_2.

WATER CIRCULATION AS AFFECTING HEAT ABSORPTION.

It is assumed that in every case the water circulates rapidly, with the utmost freedom, and with the utmost responsiveness to variations in the amount of heat absorbed, so as to keep the metal of the tube

always at water temperature. In practice this would not be true, if for no other reason than because twice the rate of heat absorption would perhaps require twice the speed of circulation; but, whereas the forces impelling circulation may, perhaps, increase directly with the increase in steam production, the retarding forces of friction increase as the square of the speed of circulation. The latter suggestions, however, are as yet only suppositions.

In each of the several calculations in the preceding table the quantity $e^{-\frac{cx_1}{D}}$ reduces to 1.0 because $x_1 = 0$; also the quantity $e^{-\frac{cx_2}{D}}$ has the constant value of 0.2295 because c and D are always the same and x_2 is taken in the table always as 10.0 feet. Therefore, the quantity in the parenthesis reduces to $(1-0.2295)=(0.7705)$. This constant is fixed once for all by the builder of the boiler when he chooses the length and diameter of the tubes. Consequently the heat absorbed by the tubes is directly proportional to the product of W and Θ_0, which represent respectively the weight of gases flowing per second and their initial elevation in temperature above that of the boiler water. All the calculations made in the case of this hypothetical boiler are for the purpose of giving specific instances showing that the product of W and Θ is very nearly constant for all reasonable conditions of good firing.

It has been stated before that the heat absorbed by a boiler is proportional to the initial temperature elevation above that of boiler water, times initial density relative to any (fixed) standard, times velocity of translation over the heating surface. A moment's reflection will make it clear that the product of the last two factors is at all times proportional to the mass (or weight) of gases passing per unit of time.

CALCULATION OF HEAT ABSORPTION ALONG A FIRE TUBE.

As an illustration of the method of using formula 9, a numerical example applied to the hypothetical boiler having a single tube of 0.1 feet internal diameter and 10 feet long is given below.

Assume that 1 pound of carbon is burned in 3,230 seconds with 25 per cent of excess of air. This is the same condition as given by the second line in the preceding table, case 1:

$$W = 0.00547 \text{ pound.}$$
$$\Theta_0 = 3{,}216^\circ \text{ F.}$$

Substituting these values, and also the value of $(1-e^{-\frac{cl}{D}})$ for this particular boiler as calculated above, in equation 9, $H = W\ \Theta_0\ (1-e^{-\frac{cl}{D}}) \times 0.24$, the heat absorbed becomes—

$$H = 0.00547 \times 3{,}216 \times 0.7705 \times 0.24 = 3{,}253 \text{ B. t. u.}$$

Instead of using formula 9, which has been derived by calculus, the amount of heat absorbed by the single-tube boiler can be approximately obtained by applying in steps the fundamental principle expressed by equation 5, $H = Cvp\ (T - t)$. Let the length of the tube be divided into twenty parts, and the heat absorbed by each part calculated by the above equation. Before these calculations can be made the constant C must be determined. This can be done by substituting in equation 9 the value of 0.5 for l, the already calculated value 0.0147 for c; and also the values of W and Θ of case 2 in the table (p. 120) and solving for H. This will be the heat absorbed by the first half foot of the tube. Substituting this value for H in equation 5 and also the calculated values for velocity, density, and the excess of temperature of the gases from tables on pages 115 and 120, and solving, we determine the value of C:

$$(9)\quad H = 0.00547 \times 3{,}216\ (1 - e^{-\frac{0.0147 \times 0.5}{.1}}) \times 0.24 = 0.291$$

$$(5)\quad 0.291 = 3{,}216 \times 19.45 \times 0.1955 \times C,$$

and hence

$$C = 0.0000238.$$

This procedure of determining the value of C had to be employed in order to put the two methods of calculating the heat absorbed on the same basis, making them comparable.

As 0.291 B. t. u. was absorbed from the gases by the first half foot, the temperature was reduced $\frac{0.291}{0.24 \times 0.00547} = 222°$ F.; the elevation of temperature above that of boiler water at the entrance to the next or second half foot of the tube $= (3{,}216° - 222°) = 2{,}994°$ F.

The absolute temperature corresponding to 3,216° above steam temperature $= 3{,}216 + 320 + 461 = 3{,}997°$ F. Likewise the absolute temperature corresponding to 2,994° F. above steam temperature $= 2{,}994° + 320° + 461° = 3{,}775°$ F. Therefore the new velocity of the gas at entrance on the second half foot of the tube is $\frac{3{,}775}{3{,}997} \times 19.45 =$ 18.38 feet per second, inasmuch as the velocities are directly proportional to the volumes. Likewise the new relative density is $\frac{3{,}997}{3{,}775} \times 0.1956 = 0.2070$. It will be noticed that the simultaneous changes in velocity and density neutralize each other, but both are carried through the calculations for the sake of the principle.

To go back to the fundamental principle, the amount of heat absorbed by the second half foot is equal to $2{,}994 \times 18.38 \times 0.2070 \times 0.0000238 = 0.272$ B. t. u.; and so on for each of the remaining eighteen half feet of the tube. On adding together all the partial H's the sum is 3.214 B. t. u., which is close to the value 3.253 obtained

by calculus. The step-by-step and calculus curves are both shown on the chart (fig. 58). The areas under these curves do not represent anything; the vertical ordinates to the curves merely denote for each small length the number of B. t. u. absorbed in that length.

On the same chart (fig. 58) is also given a curve obtained by calculus showing the amounts of heat absorbed per second when the same quantity of carbon is burned with 100 per cent of air excess.

For the sake of clearness it is stated again that the step-by-step process was merely an approximate arithmetical method of integrating the formula—

H = B. t. u. absorbed for length under consideration =

$$W\,\Theta_0 \times 0.24\left\{e^{-\frac{cx_1}{D}} - e^{-\frac{cx_2}{D}}\right\}$$

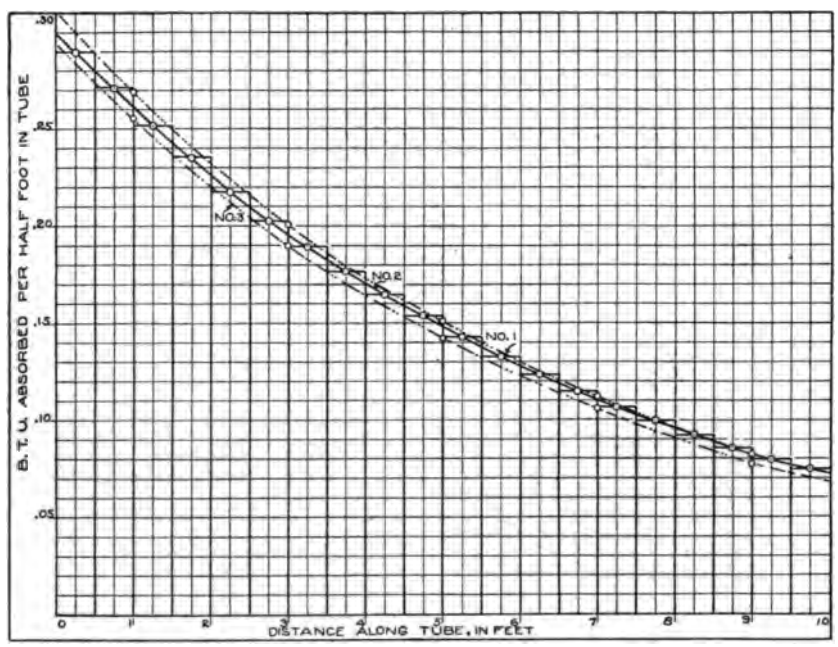

FIG. 58.—Relative B. t. u. absorbed at different points in a boiler tube 10 feet long and 0.1 foot internal diameter: Curve No. 1, calculated by calculus, using 25 per cent of air excess; No. 2, calculated by steps, using 25 per cent of air excess; No. 3, calculated by calculus, using 100 per cent of air excess

The arithmetical method gives results about 1 per cent smaller in this individual case than the integration by calculus.

Inasmuch as an illustration has been given showing how closely (within about 1 per cent) the arithmetically calculated absorption of heat agrees with the more correct value calculated by calculus when the carbon is burned with 25 per cent excess of air, the arithmetical calculation was not repeated for 100 per cent excess of air. The curves of heat absorption and of drop of temperature along the length of the boiler tube, 0.1 foot internal diameter and 10.0 feet long, are

given in figs. 58 and 59. It will be noticed that the total heat absorbed is 3.0866 B. t. u., which is only 5.2 per cent less than with the smaller air supply. This result is an illustration of the statement that a boiler will absorb about the same percentage of the heat of a pound of fuel completely burned, whatever the air supply per pound of fuel, if the variation is within reasonable limits.

The curves of temperatures along the tube, when using 25 and 100 per cent excess of air, shown on fig. 59 (p. 125), were obtained as follows: Those on the step-by-step curve were taken directly from the column headed "Θ_0" in the following table:

Heat absorption along a hypothetical boiler tube, by sections, at 25 per cent of air excess.

	Initial minus boiler-water temperature (°F.). Θ_0	Velocity of gas at entrance to each section (feet per second).[a] v	Density of gas at entrance to each section. Gas at 320°=1. p	Partial heat absorbed (B. t. u.). $H=\Theta \times v \times p \times C$.[b]
Half foot:				
First	3,216	19.45	0.1956	0.291
Second	2,994	18.38	.2070	.272
Third	2,787	17.38	.2189	.252
Fourth	2,595	16.45	.2312	.236
Fifth	2,416	15.59	.2440	.218
Sixth	2,250	14.80	.2571	.203
Seventh	2,095	14.06	.2709	.190
Eighth	1,951	13.36	.2850	.177
Ninth	1,861	12.70	.3000	.165
Tenth	1,691	12.12	.3149	.154
Eleventh	1,574	11.55	.3301	.143
Twelfth	1,465	11.02	.3460	.133
Thirteenth	1,364	10.54	.3620	.124
Fourteenth	1,270	10.09	.3780	.115
Fifteenth	1,183	9.65	.3950	.107
Sixteenth	1,102	9.26	.4110	.100
Seventeenth	1,026	8.89	.4290	.093
Eighteenth	955	8.54	.4460	.086
Nineteenth	890	8.26	.4590	.080
Twentieth	829	7.97	.4760	.075
For whole 10.0 feet				3.214
Final temperature above steam	772			

[a] Weight of gases per second in pounds $=\frac{17.67}{3230}=0.00547$.

[b] Constant=0.0000238.

The five points on the curves obtained by calculus were located by using formula 8 for five lengths of tube, 0 to 2 feet, 0 to 4 feet, 0 to 6 feet, 0 to 8 feet, and 0 to 10 feet.

HIGHER INITIAL TEMPERATURE MEANS HIGHER FINAL TEMPERATURE WHEN HEAT ABSORPTION IS BY CONVECTION ONLY.

Regarding the two curves of temperature changes along the length of the hypothetical boiler tube when using 25 per cent and 100 per cent excess of air, it appears that however long the tube might be, the upper temperature line would never meet the lower one, and would never cross it. This statement is also borne out by a consideration of the mathematical equation on which the curves are based. It is in direct contradiction to a statement often made that the higher the initial temperature the lower the final, provided the amount of heat liberated

per unit of time is the same in every case. For many months most of the authors of this bulletin thoroughly believed this idea, and it was only when they took many cases and tried to plot the relations between combustion-chamber and stack temperature that they saw the two rise and fall together. Later on the work of Perry on the boiler as a heat absorber was developed and it was realized that the facts, at the testing plant at least, agreed somewhat with the theory and pointed in the right direction. In this connection it must be remembered that a lower flue temperature does not always indicate a lower B. t. u. loss, but generally a larger one, because the mass of gases is more than enough larger to make up the difference; but in any one boiler the net difference is usually within 5 to 15 per cent.

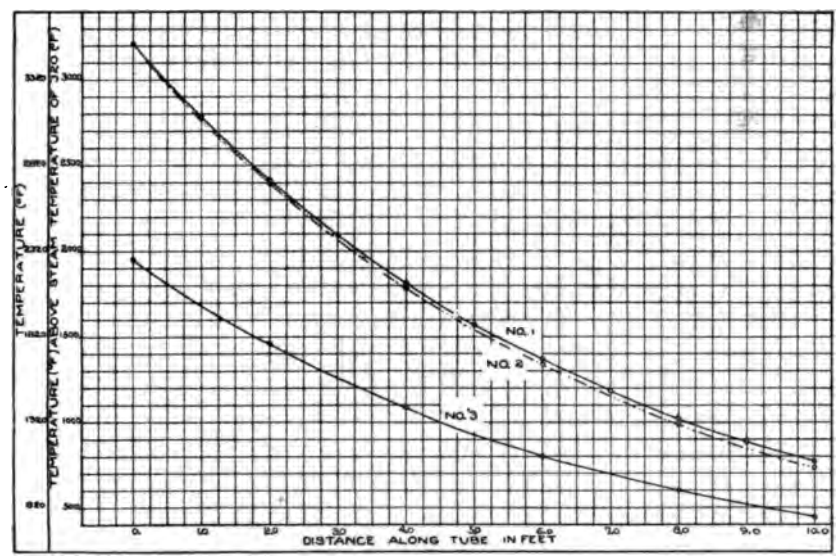

FIG. 59.—Relative temperatures of the products of combustion passing through a boiler tube 10 feet long and 0.1 foot internal diameter: Curve No. 1, calculated by steps, using 25 per cent of air excess; No. 2, calculated by calculus, using 25 per cent of air excess; No. 3, calculated by calculus, using 100 per cent of air excess.

MODIFYING FACTORS OF THE THEORY OF HEAT TRANSMISSION.

In the section on the theory of heat transmission the assumption was made that the gas comes directly into contact with the metal surface of the boiler flue, and also that the water in the boiler absorbs the heat as fast as the metal can transmit it. In a commercially operated boiler neither of these assumptions is true. The metal of the boiler flue is insulated from the gas with a layer of soot, and from the water with a layer of scale and, perhaps, a layer of steam. As these layers of soot, scale, and steam are very poor conductors, a resistance many times greater than that of the metal of the boiler tube itself is offered to the passage of heat. It is evident that under such conditions the difference of temperature between the first layer of gas and

that of the first layer of water must be greater than it would have to be if the insulating layer of soot, scale, and steam were not present, in order that the heat should flow from the gas to the water at a certain desired rate. This temperature difference must be larger the greater the required rates of heat transmission and the thicker the insulating scales. Inasmuch as capacity is the rate of heat absorption, this explains why at higher capacities the gases leave the heating surface of a boiler at higher temperatures than they do at lower capacities. It is clear, then, that in order to have the heating surface efficient it must be kept free from soot and scale, and the bubbles of steam must be removed from the surface as fast as they form, so that the water can come directly into contact with the metal. This last requirement emphasizes the importance of water circulation in the boiler. The faster the circulation of water the faster are the bubbles of steam carried away and the better is the contact between the metal and the water.

It is reasonable to expect that in the Heine boiler when the capacity is increased the rate of circulation of water should be increased in about the same proportion, in order that the metal surface may be kept free from steam bubbles. To what extent this is true is shown in the chart (fig. 7, p. 16) that gives the relation between the circulation of water in a water tube boiler and the capacity.

The effect of the above-named modifying factors—that is, the resistance offered to heat passage by soot, metal, scale, and steam—is to increase the temperature difference between the outside surface of the adhering gas film and the film of water coming into contact with the steam layer when the rate of heat transmission—that is, the capacity—increases. By taking into consideration these factors, and also the fact that the adhering film of gas does not consist of a layer 1 molecule thick, but has a sufficient thickness to offer an appreciable resistance to the passage of heat through it, a formula similar to that whose derivation is shown on pages 110 to 112 can be obtained that will agree very closely with the actual performances. Fig. 60 gives the temperature gradient of the moving gases and also the temperature gradients along the surfaces of contact of the different resistance-producing layers. Let dl be any elementary length of the heating surface; $T-t_1$ the temperature difference between the moving gases and the outside surface of the adhering film of the gas, and t_1-t the temperature difference between the latter and the water film coming into contact with the layer of steam. The temperature differences between the individual layers are expressed by a−b, b−c, etc., as shown in the figure. The heat transmission from the moving gases at the temperature T to the adhering immovable film at the temperature t_1 occurs by convection, according to the relation expressed by *equation* 1, $H=Cpv\ (T-t_1)$, and the heat transmission from the

gas film through the layers of gas, soot, metal, scale, and steam into the water at temperature t occurs purely by conduction, and follows the law expressed by equation 12:

$$(12)\ H = \frac{k}{b}(t_1 - t)$$

where k is the average conductivity for heat of the materials comprising the layers and b their total thickness. As $\frac{k}{b}$ is a constant, H varies only with the value of $(t_1 - t)$.

If the rate of heat impartation by convection is higher than the rate of transmission by conduction, the heat will accumulate in the resist-

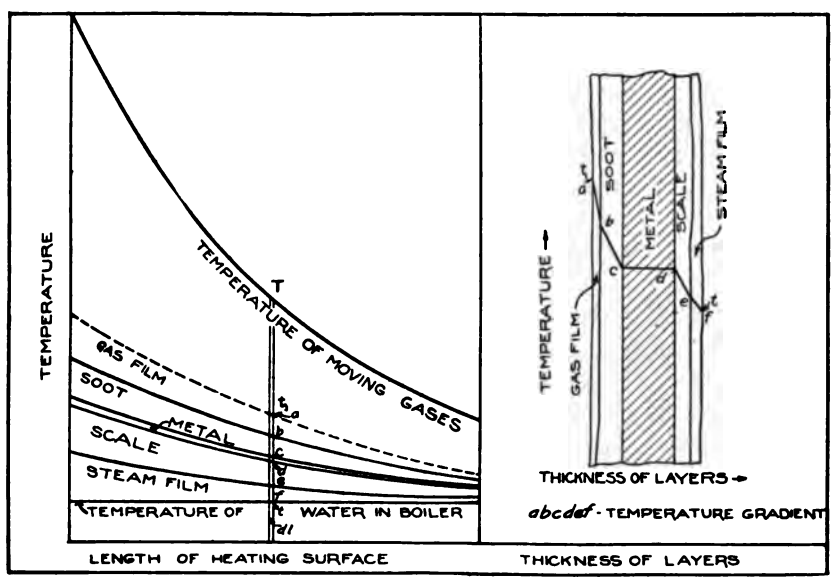

FIG. 60.—Diagrams illustrating temperature gradients of moving gases. The diagram at the left represents qualitatively the successive temperatures along the line of travel of gases through a boiler fire tube. The diagram at the right shows, qualitatively, the temperature gradients between gases and water at point T of the left diagram.

ing layers on the gas side and t_1 will rise. The rise of t_1 will decrease the rate of heat impartation by convection and increase the rate of heat transmission by conduction. The opposite will occur if the rate by convection is lower than the rate by conduction. There is a constant equalization of the two rates, so that equations 1 and 12 can be written as follows:

$$(13)\ Cpv\,(T - t_1) = \frac{k}{b}(t_1 - t).$$

The heat transmitted per second by any portion of the heating surface is then expressed by equation 1, $H = Cpv(T - t_1)$, in which T and t_1 are variables, T depending on the conditions of combustion

and the rate of heat impartation, whereas t_1 depends on the rate of heat impartation only. From equation 12—

$$t_1 = H \frac{b}{k} + t.$$

Substituting this value for t_1 in equation 1, and simplifying, we get equation 14:

$$(14) \quad H = \frac{C\,p\,v\,(T - t)}{1 + \frac{b}{k}\,C\,p\,v}.$$

Let W be the weight of gases passing the heating surface per second, then as $p = \frac{C'}{T}$ and $v = C''\,W\,T$, $C\,p\,v = C_1\,W$, where C_1 is a new constant.

Let $C_1 \frac{b}{k} = K$, and $(T - t) = \Theta$; on substituting these values in equation 14 it becomes—

$$(15) \quad H = \frac{C_1\,W\Theta}{1 + K\,W}$$

and the heat absorbed by any elementary length of heating surface per second is $-W d\Theta = \frac{C_1\,W\Theta}{1 + K\,W}\,dl$, or—

$$(16) \quad -\frac{d\Theta}{\Theta} = \frac{C_1\,dl}{1 + KW}.$$

On integrating equation 16, there results—

$$\log_e \Theta = \frac{C_1\,l}{1 + KW} + K.$$

When $l = O$, $\log_e \Theta_0 = K$. Hence

$$\log_e \Theta - \log_e \Theta_0 = -\frac{C_1\,l}{1 + KW}, \text{ or}$$

$$\log_e \frac{\Theta}{\Theta_0} = -\frac{C_1\,l}{1 + KW}$$

whence—

$$(17) \quad \Theta = \Theta_0\,e^{-\frac{C_1\,l}{1+KW}}$$

The heat absorbed by the length of heating surface equal to l is—

$$(18) \quad H = 0.24W\Theta_0\,1 - e^{-\frac{C_1\,l}{1+KW}}$$

and the true efficiency of the heating surface is—

$$(19) \quad E = 1 - e^{-\frac{C_1\,l}{1+KW}}.$$

Equation 19 states that the true efficiency of the heating surface is independent of the initial temperature of the gases so far as heat absorption by convection is concerned and that it decreases when the weight of gases passing over the heating surface increases—that is, when the capacity increases. The constant K depends on the condi-

tion as regards cleanliness of both sides of the heating surface. If there were no resistance to the passage of heat, K would be equal to O, the denominator would reduce to 1, and equation 19 would be the same as equation 10, D being constant in any one boiler, fixed once for all by the maker.

It is probable that the film of gas which is entangled in the rough sooty surface is of considerable thickness and that rather a large part of the resistance to the passage of heat is perhaps due to this film. It is also very likely that as the velocity of the gases increases their scrubbing action reduces the thickness of this film. This probably again adds to the importance of the velocity of gases along the heating surface.

The influence of the velocity of gases on the thickness of the film has not been taken into consideration in the derivation of equation 18. It would somewhat lessen the effect of W on the true efficiency; that is, it would make the true boiler efficiency more nearly constant for all rates of working.

The velocity of circulation of water in the boiler is equal in importance to the velocity of the gases on the outside of the heating surface. The same mathematical reasoning can be applied to the influence of velocity of gases on the impartation of heat. The amount of steam formed increases directly with the rate of heat transmission, and if the scrubbing action of the circulation of water is insufficient to remove it from the heating surface the resistance due to the layer of steam formed will rise with the rate of making steam. Lack of adequate circulation of water in a boiler is a check to capacity. The fact is becoming well known that small automobile boilers are making steam ten to twenty (or even more) times as fast per unit of heating surface as stationary boilers in power plants, and at better efficiency. This increased rate of steaming is attained purely by high velocity of water and steam circulation over the heating surface.

Formulas 17, 18, and 19 apply only to heat imparted to the boiler by convection and conduction. The heat which is received by radiation perhaps follows nearly the radiation law of Stefan and Boltzmann, expressed by equation 20,

$$\textbf{(20)}\quad H = C\,(T^4 - t_1^4),$$

where T is the absolute temperature of the heat-radiating body, t_1 the absolute temperature of the heat-receiving body, and C a constant.

In the case of a boiler, t_1 is the temperature of the outside layer of soot on the heating surface, and is a variable, depending on the rate of heat transmission through the sooted and scaled boiler plate. The heat transmitted through the boiler plate is given by equation 12, $H = \frac{k}{b}(t_1 - t)$. As the heat transmitted through the boiler plate is

equal to the heat received by the surface of the plate by radiation, equations 12 and 20 can be written as follows:

$$C\,(T^4 - t_1^4) = H = \frac{k}{b}\,(t_1 - t).$$

On substituting the value of t_1 from equation 12 in equation 20, the latter becomes—

$$(20)\quad H = C\left[T^4 - (H\,\frac{b}{k} + t)^4\right].$$

This is an equation of the fourth degree, and the value of H can be obtained by the method of approximation.

By the use of equations 18 and 20 it is possible to obtain the total heat absorbed by any boiler and its true efficiency. However, before the equations can be used the constants in them must be determined for any particular boiler. The four constants in the two equations were determined for the Heine boilers at the fuel-testing plant in this way: Four specific cases were selected from the results of boiler trials and from the resulting equations the values of the constants were approximated. The two equations applied to these Heine boilers are—

$$(18)\quad H_c = 0.24W\Theta_0\,(1 - e^{-\frac{2.7}{1+0.1524W}}),\ \text{and}$$

$$(20)\quad H_r = \frac{1}{540 + 10^8}\left[T^4 - \left(\frac{H}{0.145} + t\right)^4\right];$$

where t at 80 pounds gage pressure is 785° F. absolute and Θ_0 is $T - t$, T being the actual absolute temperature in the furnace in degrees Fahrenheit; H_c the heat received per second by the boiler by convection and conduction; H_r the heat received per second by radiation from the brickwork, etc., of the combustion chamber; and W the weight of gases in pounds passing over the heating surface per second. Within the workable temperature range from 2,461° to 3,361° F. absolute, H_r is obtained with fair accuracy by the simple straight-line equation—

$$(21)\quad H_r = 0.144T - 294.$$

The per cent of heat received by radiation referred to total heat available is—

$$(22)\quad E_r = \frac{(0.144T - 294) \times 100}{0.144T - 294 + 0.24W\Theta_0}$$

and the per cent of heat received by convection referred to total heat available is—

$$(23)\quad E_c = 100\,(1 - e^{-\frac{2.7}{1+0.1524W}}) \times (1 - E_r).$$

The true boiler efficiency is then expressed by equation 24:

$$(24)\quad E_4 = E_r + E_c.$$

Heat which is radiated to the boiler during the combustion of fuel is not sensible heat, because it does not raise the temperature of the gases. This is the reason why the heat radiated is added to the

heat in the gases at the temperature T to obtain the total heat available for the boiler. E_r has been calculated by formula 22 for five values of W and the results are plotted on the lower part of fig. 61. $\left(\frac{E_c}{1-E_r}\right)$ has been calculated by equation 23 and the results are plotted on the upper part of fig. 61. The true efficiency of these par-

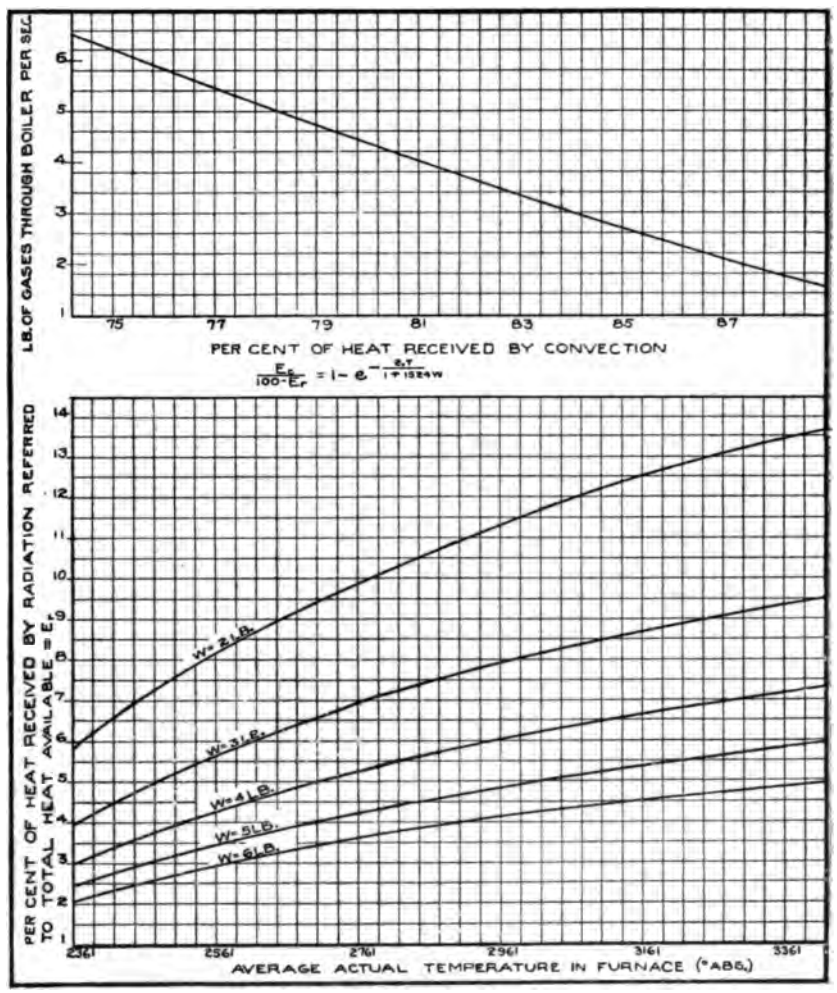

FIG. 61.—Relation of pounds of gases passing through boiler per second to per cent of heat received by convection (upper curve); also the relation between ratio of per cent of heat received by radiation to total heat available and the average actual temperature (degrees F. absolute) in furnace (five lower curves).

ticular Heine boilers can be obtained for any condition within the practice of operation by a simple multiplication and addition.

Example 1. Let 5 pounds of gases pass over the heating surface in a second, and let the actual furnace temperature be 2,961° F. abso-

lute. In fig. 61 (lower part), where $W = 5$ pounds and $T = 2{,}961°$ F. absolute, $E_r = 4.85$. In the upper curve of fig. 61, where $W = 5$ pounds, $\frac{E_c}{100 - E_r} = 78.15$. Then $E_4 = E_r + E_c = 4.85 + 78.15 \times (100 - 4.85) = 79.15$.

Example 2. Let $W = 3$ and $T = 3{,}261°$ F. absolute. Then $E_r = 9$ and $\frac{E_c}{100 - E_r} = 84.2$. $E_4 = E_r + E_c = 9 + 84.2 \times (100 - 9) = 85.62$.

Example 3. Let $W = 5$ pounds and $T = 3{,}261°$ F. absolute. Then $E_r = 5.6$ and $\frac{E_c}{100 - E_r} = 78.15$. $E_4 = E_r + E_c = 5.6 + 78.15 \times (100 - 5.6) = 80.4$.

In examples 2 and 3 the capacities are to each other very nearly as 3 is to 5; that is, if the capacity is 90 per cent in example 2 it is nearly 150 per cent in example 3.

Equations 18 to 24 are rational formulas, and are interesting because they are derived purely by mathematical reasoning from the fundamental laws of physics—that is, the laws of convection, conduction, and radiation of heat. It is gratifying that the actual performance of two individual boilers throughout wide ranges of furnace temperature and rates of combustion has been very closely approximated by a formula based on fundamental principles of physics—the laws of the kinetic theory of gases and liquids and of the transfer of heat by conduction and radiation.

TEMPERATURE TEST OF PERRY'S EQUATION.

For the purpose of testing Perry's equation, that "The temperature above boiler water of the gases entering a boiler = the temperature above boiler water of gases leaving the boiler, times a constant," all tests on which approximate combustion-chamber temperatures were taken by a Wanner optical pyrometer were used—a total of 215 tests. For convenience, the temperature of the water in the boiler was assumed to have been always 317° F. This temperature varied 5° or 6° in different tests. The resulting constants, which ranged from 4 to 14, were collected in groups, showing that two fall between 4.5 and 5, six between 5 and 5.5, nineteen between 5.5 and 6, etc. These relations, plotted on the chart (fig. 62), show that the peak comes at 7.25; the arithmetical average of all the values is 7.43. It will be noticed on the curve that there are more high values than low values, whereas a true probability curve is symmetrical on both sides of the vertical axis.

On looking up the high values, especially those between 10 and 10.5, the average point of which is rather high, it is found that they belong to tests having flue temperatures that are suspiciously low for various reasons. But leaving in this point and casting out the six tests hav-

ing the highest values of the constant (all of which have the suspiciously low flue temperatures), the remaining 209 tests average 7.3—about the same value as that of the peak of the curve.

This means that if the excess of combustion-chamber temperature above steam temperature be divided by 7.25 the quotient will be the probable excess of flue temperature above steam temperature. This

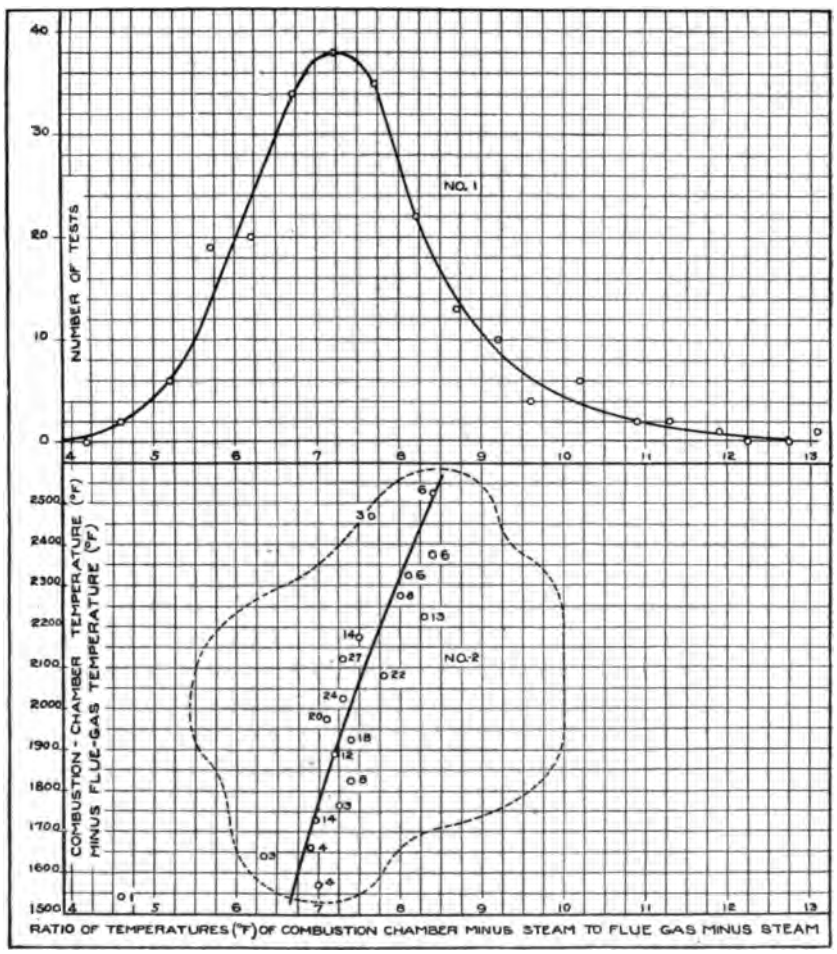

FIG. 62.—Classification on basis of ratio of temperatures of combustion chamber minus steam to flue gas minus steam: Curve No. 1, probability curve of ratio (maximum point, 7.25); No. 2, relation of ratio to combustion-chamber temperature (°F.).

result is now to be compared with the "true boiler efficiency," which was tentatively found to be 82.7 per cent. The calculation to be made assumes that the specific heat of the gas mixture is constant up to 2,500° F., which is probably not true. It is also assumed that no cold air leaks into the gas stream between the entrance to the boiler and the flue, which we know is far from true.

On the assumption that the initial temperature of the gases is 2,500° F., this is 2,500° − 317° = 2,183° F. above steam temperature; 2,183° divided by 7.25 = 301° F. the probable excess of flue temperature over boiler-water temperature. Now, out of the maximum possible 2,183 B. t. u. that might be absorbed by a boiler from each 4.15 or ($\frac{6}{7}$) pound of furnace gases, this boiler absorbed 2,183 − 301 = 1,882 B. t. u., which is 86.2 per cent of 2,183. That is, the true boiler efficiency calculated from initial and final temperature of gases is 86.2 per cent, which is fairly close to the 82.7 per cent found above.

Into this method of calculating the "true boiler-efficiency constant" there enter two errors, which will be roughly corrected in a specific calculation. The combustion-chamber temperature, as read by the optical pyrometer, is known to have been usually low. In this calculation it will be assumed that the pyrometer read 100° low, making the true initial temperature 2,600° F.; also it will be assumed that the air which leaked through the etting amounted to 20 per cent in mass of the gases which entered the boiler, which is an approximately true average, and that all of this air entered the stream of gas after leaving the boiler and before reaching the flue thermometer, which is not true.

The initial temperature is 2,600° − 317° = 2,283° F above steam temperature. If we use the old constant, 7.25, the flue temperature should be 2,283° F. ÷ 7.25 = 315° F. above steam temperature, which would make the flue temperature 632° F., say 630°. Remembering that this 630° is the result of the cooling of the gases by the boiler and also of the addition of cold air at 60° F. to the extent of 20 per cent, we can calculate that the flue temperature would have been about 768° F. had this admixture not occurred. Subtracting 317° from 768°, we have left 451° F. Thus out of the maximum 2,283 B. t. u., which a boiler might possibly be built to absorb from every 4.16 pounds of gases, this boiler absorbs 2,283 − 451 = 1,832 B. t. u., which is 80.3 per cent of 2,283. That is, the true boiler efficiency thus approximated by initial and final temperature of furnace gases is 80.3 per cent; before correction it was 86.3 per cent. The mean is close to the value 82.7 found by the entirely different heat-balance method.

RATIO MODIFIED IN PRACTICE BY INITIAL TEMPERATURE.

The lower curve of fig. 62 (p. 133) was formed for all the individual tests from the same ratios as the upper curve. The ratios of excess of furnace temperature to excess of flue-gas temperature were all plotted preliminarily on a sheet of coordinate paper, and the average value of the ratios falling in each horizontal temperature strip 50° wide was determined. These average values are given by the positions of the small circles, the number beside each giving the number of tests falling in that horizontal temperature strip. It will be noticed that the heavy line, drawn through the points from these averages

with regard to their respective weights, slopes upward to the right—that is, with the higher furnace temperatures the boilers absorb a slightly larger portion of the heat available to them, only that heat in the gases which is above steam temperature being considered as available. The dotted line marks the boundary of the field covered by the individual ratio points.

As a numerical example let us take two cases and figure backward from the ratios to the "true boiler efficiencies."

Case 1: From the curve (the lower one) we see that when the temperature of the combustion chamber minus steam temperature equals 1,700° F., the ratio averages 7.0. Dividing 1,700° by 7.0, we get 243°, the average excess of the flue temperature above steam temperature at this initial-temperature excess.

$$\frac{1{,}700-243}{1{,}700}=85.7 \text{ per cent} = \text{true boiler efficiency.}$$

Case 2: From the same curve take initial temperature excess = 2,400° F.; the ratio is 8.2; $2{,}400 \div 8.2 = 293°$, the average excess of flue temperature over steam temperature under these conditions.

$$\frac{2{,}400-293}{2{,}400}=87.7 \text{ per cent} = \text{true boiler efficiency.}$$

The value in the first case was 85.7 per cent. The second case then gives an increase of 2 per cent of the heat which could possibly be absorbed.

One tentative explanation of this slight increase of efficiency at higher temperatures is that the boiler absorbs heat not only by convection from the gases among its tubes, an action to which Perry's tentative theory is applicable, but also, more or less, by radiation from the bottom and sides of the combustion chamber onto the bare tubes in the rear, where the gases leave the combustion chamber. This radiation does not increase directly with the furnace temperature, but varies as the difference of the fourth powers of the absolute temperatures of the radiating and receiving bodies. That is, if T_F represents the absolute temperature of the furnace walls "visible" to the exposed tubes, and T_T the absolute temperature of the outer surface of the cold tubes, the heat absorbed by the tubes due to radiation is proportional to $(T_F^4 - T_T^4)$. It is easily seen that inasmuch as T_T is practically constant, changes in T_F will change the value of the parenthesis a great deal. Consequently, as the temperature of the combustion-chamber walls rises the amount of heat absorbed by the exposed portion of the lower row will increase much more rapidly; and though this heat is only a part of the total heat absorbed by the whole boiler, its rapid rate of increase may raise the "true boiler efficiency" a little.

The lower curve of fig. 62 (p. 133) bends to the right as it ascends. If the radiation increased directly as the temperature difference

between the furnace walls and bare tubes, the line might well be straight; but as it increases according to the fourth-power law, the curve should bend to the right.

Thus by two entirely different and independent methods we have arrived at the conclusion that the true efficiency of these boilers is nearly constant. These methods are the heat-balance method described on pages 139–141, and the excess-temperature-ratio method just given. On pages 143–145 another independent method arriving at

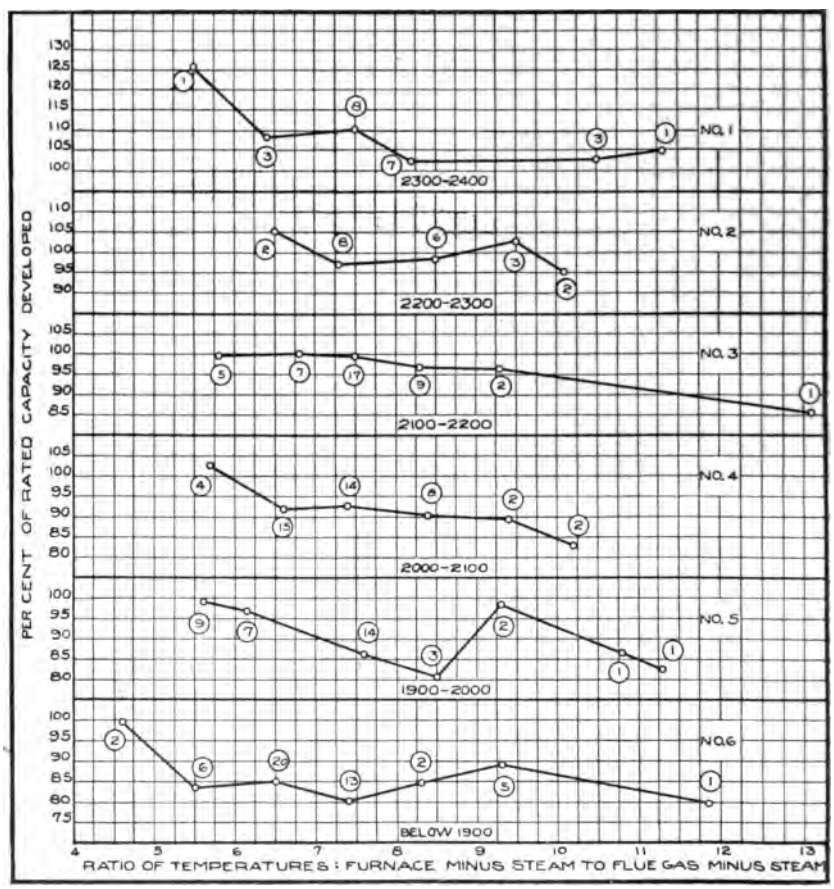

FIG. 63. Relation between ratio of furnace temperature minus steam temperature to flue-gas temperature minus steam temperature and per cent of rated capacity, based on varying values of furnace temperature minus steam temperature.

the same conclusion is given, with the additional refinement that true boiler efficiency increases slightly not only with increase of furnace temperature, but also with decrease in the amount of steam made. It must be distinctly understood that all these ideas are advanced tentatively only, as another attempt to separate furnace and boiler.

The indication that the true boiler efficiency is so nearly constant and so little affected by initial furnace temperature is gratifying, as

suggesting that some such formula as Perry's must be nearly correct. Thus encouragement is given to the hope that there is a way to determine once for all one constant boiler efficiency, from which we can calculate backward and obtain the combustion efficiency or per cent of completeness of combustion—the vital point in fuel testing. This applies only to boilers obtaining their heat by convection, not by radiation.

Fig. 63 is based on exactly the same data as those of fig. 62 (p. 133), which are elsewhere explained. It is intended to show the relation of flue-gas temperature to capacity when the furnace temperature remains nearly constant. The tests were arranged in six groups in such a way that the variation of the furnace temperature was less than 100° F. in each group.

The tests in each of these groups were then classified on the basis of the ratio of temperature of furnace minus that of steam to temperature of flue gas minus that of steam, and this ratio was plotted against the average capacity of each class.

The curves show a general tendency of the capacity to rise with the low-temperature ratios. This is in accordance with equation 17; as the furnace temperature remains nearly constant, higher capacities are obtained by increasing the weight of gases passing over the heating surface per second. The increase of the weight of gases causes, according to equation 17, the rise in flue-gas temperature.

In other words, this rise of flue-gas temperature is probably due to two causes: (1) When more heat is put through the outer gas film, soot, metal, scale, and inner steam film or bubbles the temperature gradient must necessarily be steeper, and since the conductivity of all these layers except the metal is low, the rise of temperature of the outer soot layer and its entangled gases may be several hundred degrees, whence it becomes a less active heat absorber, and consequently the gas escapes at a higher temperature, so that the efficiency of the boiler is less. (2) As shown in fig. 7 (p. 16), the circulation of water does not keep up to requirements, so that the steam film on the scale becomes thicker, or more of the surface is covered with bubbles, which again makes the boiler a poorer heat absorber.

A CONCEPTION OF BOILER AND FURNACE EFFICIENCY.

THE CODE FORM AND A REVISED FORM OF HEAT BALANCE.

The "boiler efficiency" given in the A. S. M. E. code as item 72* is the ratio of the heat absorbed in the boiler and carried away in the steam to the highest possible amount of heat that could be generated in the furnace. The denominator of this ratio is calculated by subtracting from the total pounds of "combustible" fired the number of pounds of combustible in the ash and multiplying this difference by the calorific value of 1 pound of "combustible."

The efficiency represented by code item 72* is, then, the over-all efficiency of the whole steam-generating apparatus, as combustible found in the ash is considered as if it had never been fired. It often happens that, on account of incomplete combustion, the quantity of heat represented by the denominator of the above ratio is not really developed in the furnace. Carbon monoxide in the analysis of the stack gases is one indication of this incomplete combustion.

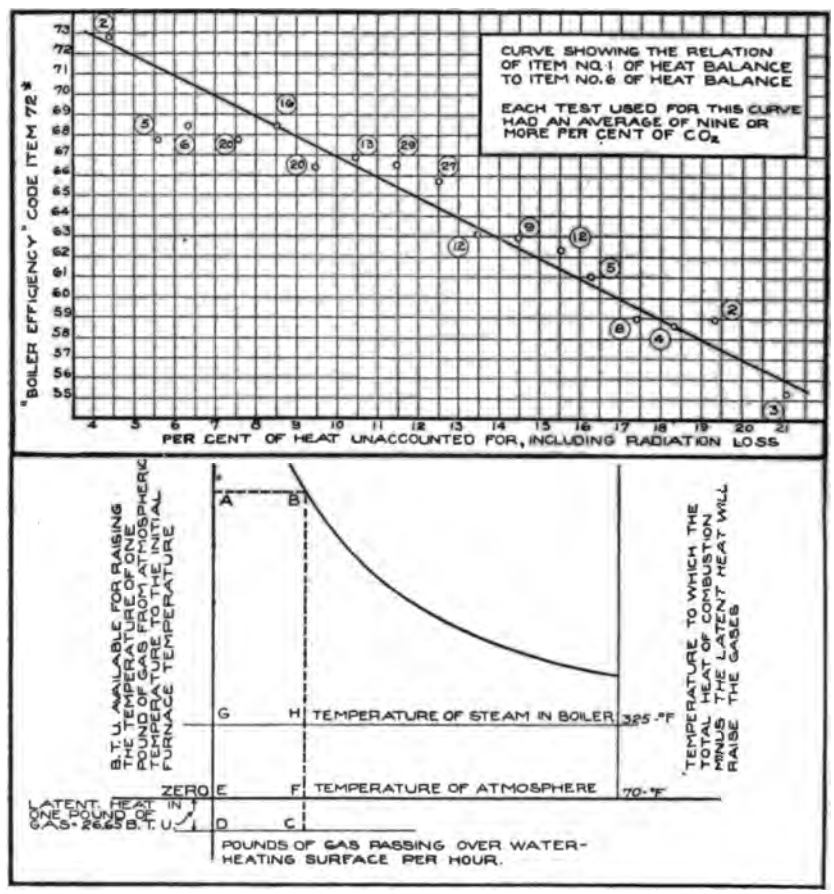

FIG. 64.—Relation of unaccounted-for loss, including radiation loss (upper curve) to boiler efficiency (code item 72*); and availability of heat to a boiler, as affected by changes in air supply to fuel (lower curve).

The ratio of the heat that is actually generated in the furnace to the maximum amount of heat that could be developed may be called the efficiency of the furnace or the furnace efficiency. The ratio of the heat absorbed by the boiler and carried away in steam to the heat actually generated from the burning of the fuel may be termed the boiler efficiency, and represents the ability of the boiler to absorb heat under given conditions. The efficiency given by code item 72* is the product of the boiler and furnace efficiencies as above defined.

Carbon monoxide is not the only resultant of incomplete combustion, although the heat lost by it is the only loss due to incomplete combustion that has been taken account of in the heat balance. The remainder of the incomplete combustion losses appear in the "unaccounted for." A high unaccounted-for loss, then, should be an indication of low furnace efficiency.

The upper curve of fig. 64 shows the relation between "boiler efficiency" (code item 72*) and the unaccounted-for loss plus radiation loss (heat balance, item 6). All the tests chosen for this chart have an average of 9 per cent or more of carbon dioxide in the escaping gases, which indicates that they must all have had comparatively high furnace temperatures. It has always been thought that when a high furnace temperature is maintained the boiler would absorb a high per cent of the heat developed in the furnace; therefore, the boiler efficiency as defined above must have been relatively high for all the tests of this chart.

It will be noticed that the sum of the ordinate and abscissa for any point of this curve is constant at 77 per cent. For instance, when item 72* is 73 per cent the unaccounted-for loss is 4 per cent; sum, 77 per cent. When item 72* is 57 per cent, the unaccounted-for loss is 20 per cent; sum, 77 per cent. The curve should have been drawn more nearly horizontal for the low unaccounted-for values.

The decrease of the combined efficiency of boiler and furnace (code item 72*) with the increase of the unaccounted-for loss must then be due to the decrease of furnace efficiency.

With this idea of furnace efficiency in mind, a new form of heat balance, shown below, is compared with the heat balance given in the A. S. M. E. code.

Heat balance as given in the code.

	Per cent.
1. Heat absorbed by boiler	60.30
2. Loss due to moisture in coal	.26
3. Loss due to moisture formed by burning of hydrogen	4.09
4. Loss due to heat carried away in dry chimney gases	14.96
5. Loss due to incomplete combustion of carbon (CO loss)	2.17
6. Loss due to unconsumed hydrogen and hydrocarbons, to heating the moisture in the air, to radiation, and unaccounted for	18.22

A revised form of heat balance.

1. Heat absorbed by boiler	60.30
2. Loss due to moisture in coal	.26
3. Loss due to moisture formed by burning of hydrogen	3.26
4. Loss due to heat carried away in dry chimney gases	11.93
5. Loss due to radiation	3.97
Total heat generated	79.72
6. Loss due to incomplete combustion of carbon (CO loss)	2.17
7. Loss due to other forms of incomplete combustion	18.11

In the new heat balance the subtotal 79.72 represents the per cent of the calorific value of the fuel that has been generated. It may be taken as the efficiency of the furnace, or, to speak more properly, the per cent of completeness of combustion. The latter phrase will be used in this discussion for this subtotal, which is defined as the ratio of the heat generated by burning a unit weight of combustible in the furnace to the heat obtained by burning the same weight of combustible in the calorimeter. This efficiency is designated elsewhere in this bulletin by the symbol E_3.

The method of determining the radiation loss is given on page 143. It is noticed that items 3 and 4 are smaller in the revised heat balance than in the heat balance of the code. This is because they have been multiplied by the per cent of completeness of combustion. This correction was made on the assumption that if only 79.72 per cent of the calorific value of the fuel was realized, only 79.72 per cent of each constituent of the moisture and ash-free coal was burned. This may not be the state of affairs in incomplete combustion, but the assumption furnishes a basis for calculations and perhaps the correction made on this assumption reduces the error of the calculation within the limits of accuracy of the analysis of the escaping gases.

In the revised heat balance the ratio of 60.30 to 79.72 is the boiler efficiency, which may be defined as the ratio of the heat absorbed by the boiler and carried away in the steam to the heat actually generated by the burning of the fuel. This ratio is elsewhere in this bulletin designated by the symbol E_5. The product of the furnace and boiler efficiencies is the efficiency of the boiler and furnace combined and is the same as that given in the code as item 72*. As explained above, this combined efficiency may be considered as the over-all efficiency of the steam-generating apparatus if the combustible in the ash is considered as not being fired.

As the calculations for these charts are somewhat lengthy, one test has been taken as an example and the calculations for it are given at the end of this discussion. The number of pounds of gas passing over the water-heating surface per hour and also the theoretical initial temperature of the gas have been calculated for each test. The term initial temperature is used in this paper to mean that temperature to which the gases would rise if it were possible to prevent loss of heat from them by either conduction or radiation until all combustion had ceased. In figuring the initial temperature it was assumed that the specific heat remains constant.

All the steaming tests made at the testing plant were arranged in groups according to per cent of rated capacity, as follows: 65 to 75, 75 to 85, 85 to 95, etc. Then the tests of each of these groups were rearranged according to their calculated initial temperatures into the

following groups: 1,600° to 1,800° F., 1,800° to 2,000° F., 2,000° to 2,200° F., etc. Each of these 40 smaller groups was averaged for (1) initial temperature (calculated); (2) pounds of gas passing over the water-heating surface per hour; (3) percentage of rated capacity developed; (4) boiler efficiency (E_5), and (5) true boiler efficiency (E_4). The first four averages for each group were considered as

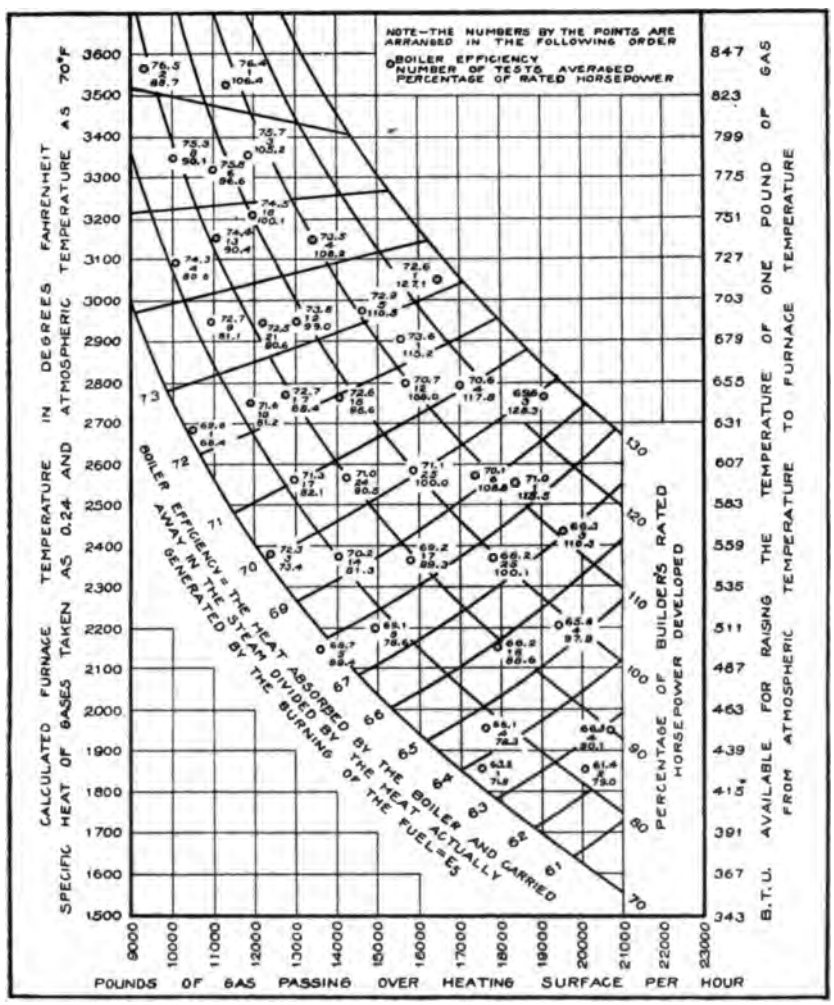

FIG. 65—Curves of constant boiler efficiency (E_5) and of constant capacity developed.

data of one representative test and were plotted on the chart shown in fig. 65, and the first three and the fifth in fig. 66.

DERIVATION OF THE CONSTANT-CAPACITY CURVES OF FIG. 65.

Each of the above forty representative tests was plotted on rectangular axes, the theoretical temperatures being used as ordinates (see fig. 65) and the number of pounds of gas passing over the water-

heating surface per hour as abscissas. When a point was located it was marked with the average capacity, the number of actual tests that were averaged, and the average boiler efficiency E_5. (See note at top of the chart.) In the upper left-hand corner there is a point which is marked "76.5, 2, and 88.7." This means that two tests were averaged, that the average E_5 was 76.5, and that the average capacity was 88.7 per cent of the builder's rated capacity; and the position of the point on the chart shows that the average number of pounds of gas passing over the water-heating surface per hour was 9,300. When the forty representative tests were plotted in this manner it was found that lines of constant capacity could be drawn through these points. The lines extending from the upper left-hand corner to the lower right-hand corner of the chart are these constant-capacity lines. They are labeled with their respective percentages of rated capacity developed.

DERIVATION OF BOILER EFFICIENCY (E_5).

Moisture is always present in the products of combustion, and it takes an appreciable amount of the heat generated in the furnace to convert this from water into steam. The rest of the heat generated goes to raising the temperature of the gases. It was found that the average amount of latent heat in 1 pound of the escaping gases was 26.65 B. t. u., which is enough to raise the temperature of 1 pound of gas 111° F. In these calculations the specific heat of the dry gases was taken as 0.24 for all temperatures and the specific heat of steam as 0.48. On this assumption the same amount of heat is used to raise the temperature of 1 pound of steam 1° as is required to raise the temperature of 2 pounds of dry gases 1°, so in order to use 0.24 as the specific heat of all the products of combustion the number of pounds of steam in the gases was multiplied by 2.

Let the lower curve of fig. 64 (p. 138) be one of the constant-capacity curves shown in fig. 65. The scale to the left of the chart represents the B. t. u. available for raising the temperature of 1 pound of gas from atmospheric to furnace temperature. The theoretical furnace temperatures to the right of the chart are obtained by dividing by 0.24 the B. t. u. available for raising the temperature of 1 pound of gas and adding to the quotient the temperature of the atmosphere, which is taken as 70° F. The line CD is drawn in such a manner that the distance ED represents on the scale to the left 26.65 B. t. u., which was found to be the average amount of latent heat in 1 pound of furnace gas. The area ABCD represents the total heat generated in the furnace; the area CDEF shows the latent heat in the gases and the area ABEF shows the heat available for raising the temperature of EF pounds of gas from 70° F. to the initial furnace temperature A. Since the curve is one representing constant capacity, the heat absorbed

by the boiler in all tests on this curve will be a constant and this constant divided by the area ABCD will be the boiler efficiency E_5 for the point B. By using the ratio of the constant heat absorbed by the boiler to the area ABCD, those positions of B which represent efficiencies 61, 62, and 63 per cent, etc., were found. By this means lines of constant-boiler efficiency (E_5) were found and drawn on the chart (fig. 65). It will be noticed that the efficiency of the plotted points generally falls within about 1 per cent of their allotted position as determined by these constant-efficiency lines.

DERIVATION OF TRUE BOILER EFFICIENCY (E_4).

The constant-capacity lines are of the form $xy^n = \text{constant}$, where x = number of pounds of gas passing over the water-heating surface per hour and y = the calculated initial temperature. The curves are all asymptotic to the lines $x = 0$ and $y = 325°$ F. (See fig. 64.) The temperature of the steam in the boiler at about 80 pounds pressure is 325° F. Now, if the boiler were infinitely long and there were no heat lost in radiation, the boiler could never cool the gases below a temperature of 325° F. In other words, only the heat represented by the area ABGH is available to the boiler. The ratio of the heat absorbed by the boiler and carried away in the steam (which is constant for any point on the constant-capacity line) to the heat available for the boiler, area ABHG, has been termed the true-boiler efficiency (E_4). (This definition of E_4 differs very slightly from the one finally chosen, for which see glossary, p. 182.)

This efficiency E_4 has been calculated for each test and the method used is shown with the other calculations on page 145. The chart shown in fig. 66 is similar to that of fig. 65 in every respect except that E_4 is used instead of E_5.

METHOD OF ESTIMATING RADIATION.

It was necessary to devise some method for estimating the radiation losses in order to calculate the per cent of completeness of combustion (E_3). The method used was very crude and was based on the following reasoning:

The radiation from the top of the boiler drum and the front and rear water legs is very nearly constant and was determined as follows: With no fire under the boiler the uptake was closed by laying boards across the opening at the base of the stack and covering them with cement. This prevented any air from going up the stack. The fire doors and ash pit were bricked up to prevent air from entering the setting. After drawing the water out of the boiler it was filled with steam from another boiler carrying 80 pounds pressure. This pressure was maintained until the temperature in the combustion chamber became constant. The amount of condensed steam per hour was

then weighed and was taken as a measure of the heat radiated per hour. The radiation from the brick setting and fire doors was considered to increase with the capacity. When the boiler developed 90 per cent of its rated capacity the variable radiation was taken as three-fifths and the constant radiation as two-fifths of the total heat radiated. The increase of the variable radiation with capacity was such as to

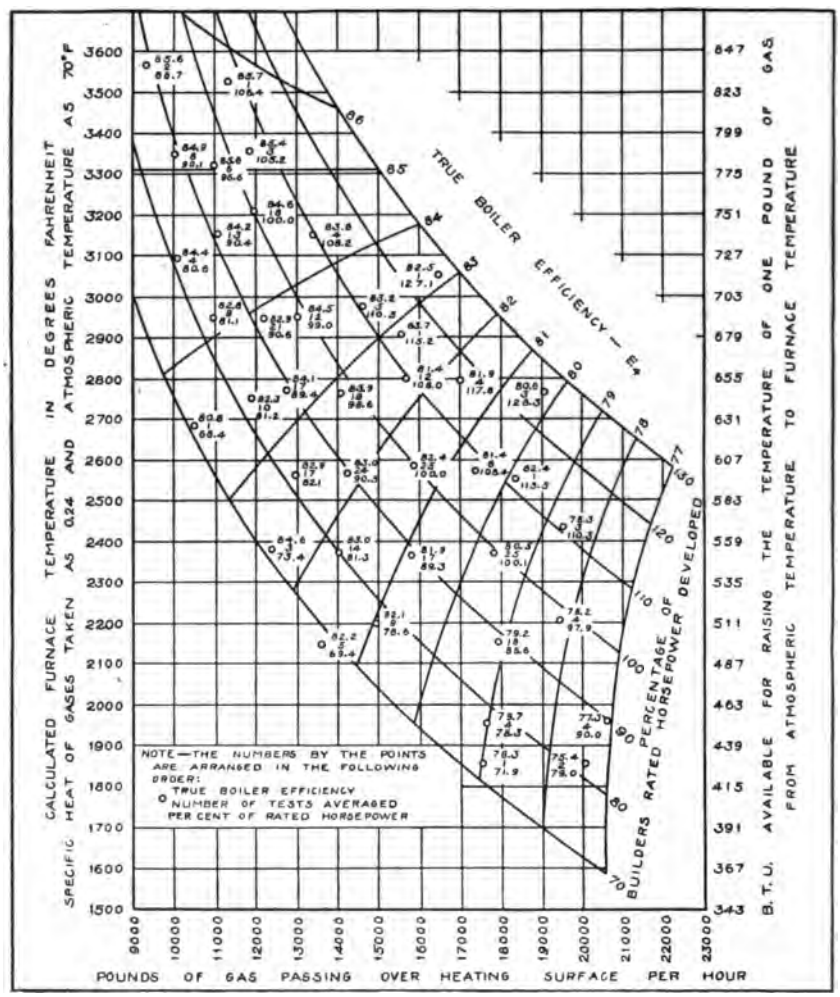

FIG. 66.—Curves of constant true boiler efficiency (E_4) and of constant capacity developed.

make the total B. t. u. radiated per hour 395,000 at 50 per cent of the rated capacity and 500,000 B. t. u. at 120 per cent of the rated capacity. A chart (not given here) was drawn having B. t. u. radiated per hour as ordinates and per cent of the rated capacity developed as abscissas, and the two above points were plotted on it. By connect-

ing these points with a straight line the B. t. u. radiated per hour could be estimated for any capacity.

The heat required to change 1 pound of water at 70° F. to steam at 212° F. $= (212-70)\times 1+966=142\ (0.48+0.52)+966=(0.48\times 142)+(0.52\times 142)+966=68+74+966=68+1{,}040$.

The heat required to raise 2 pounds of dry gas from 70° F. to 212° F. $=(212-70)\times 0.24\times 2=68$.

It is evident from the above that 1,040 more B. t. u. are required to change 1 pound of water from 70° F. to steam at 212° F. than are required to raise 2 pounds of gas through the same range of temperature. However, at any temperature above 212° F. the same amount of heat is required to raise the temperature of 2 pounds of gas 1° F. as is required to raise the temperature of 1 pound of steam 1° F. Therefore in calculating the total heat and the initial temperature of the gases, 1 pound of water may be considered as the equivalent of 2 pounds of dry gas, provided that in the case of the 1 pound of water account is taken of the 1,040 B. t. u. which are not available for raising temperature.

The following calculations were made on test 216, the heat balance of which is given on page 139:

Calculations based on test 216 to deduce a better heat balance.

Per cent of completeness of combustion (E_3):	Per cent.
Per cent of rated capacity developed	103
Calorific value of 1 pound of "combustible" taken as	100
A. Heat absorbed by boiler (heat-balance item 1)	60.30
B. Heat carried away in moisture of coal (heat-balance item 2)	.26
C. Heat carried away in moisture formed by burning hydrogen (heat-balance item 3)	$(4.09\div 100\times E_3)$
D. Heat carried away in dry gases (heat-balance item 4)	$(14.96\div 100\times E_3)$
E. Heat lost in radiation	3.97
E_3 (per cent of calorific value of fuel that has been generated)$=A+B+C+D+E$	79.72
Boiler efficiency (E_5)$=A\times 100\div E_3$	75.64
Total pounds of equivalent dry gas passing over water-heating surface per hour:	Pounds.
F. Moisture in coal for every pound of "combustible" (figured from proximate analysis)	0.03
Hydrogen per pound of "combustible" (ultimate analysis)	.0543
G. Moisture formed by burning of hydrogen$=9\times 0.0543\times E_3$	.39
H. Total moisture in gases formed from 1 pound of "combustible"$=F+G$	.42
Dry gas per pound of "combustible," assuming $E_3=100$ (figured from gas analysis)	18.35
I. Actual dry gas per pound of "combustible" as fired$=18.35\times E_3$	14.63
J. "Equivalent" dry gas per pound of "combustible" as fired$=I+(2\times H)$ (see discussion of calculations)	15.47
Total combustible ascending from grate per hour (code item 47*)	775.0
Total equivalent dry gas passing over the water-heating surface per hour$=15.47\times 775.0$	11,990

	B. t. u.
Heat in gases below 325° F. (steam temperature):	
K. Heat in the gases, from 1 pound of "combustible," which is unavailable for raising temperature=H×1,040 (see discussion of calculation)..	437
L. Heat required to raise the temperature of gases formed from 1 pound of "combustible" taken from 70° F. to 325° F.=J × 612.....	947
M. Total heat below 325° F. in the gases from 1 pound of "combustible"=K+L.....	1,384
Heat above 325° F. in the gases from 1 pound of "combustible"—that is, heat available to the boiler:	
Calorific value of 1 pound of "combustible" (item 51).....	15,423
N. B. t. u. generated from 1 pound of "combustible"= E_3 × 15,423....	12,295
O. Heat available for the boiler per pound of "combustible"=N−M...	10,911
True boiler efficiency (E_4):	
P. Heat absorbed by the boiler per pound of "combustible" (from heat balance).....	9,300
E_4=P÷O=85.23 per cent.	
Theoretical initial temperature:	
Heat above 325° F. in 1 pound of gas=O÷J.....	705.3
705.3 B. t. u. will raise the temperature of 1 pound of gas 705.3÷0.24, or 2,939° F.	
Initial temperature = 2,939°+ 325°= 3,264° F.	

As explained in the discussion on page 140, the calculated initial temperature as given by the scale to the left of figs. 65 (p. 141) and 66 (p. 144) is that temperature to which the gases would rise provided no heat were lost by conduction or radiation until combustion had ceased, 0.24 being used as the specific heat of the gases at all temperatures. However, these conditions never exist in practice. A large amount of heat is lost from the gases by both conduction and radiation before combustion ceases; furthermore, the specific heat of the gases at high temperature may be higher than 0.24. For these reasons the calculated furnace temperature is much higher than that actually attained.

In order to obtain a calculated initial temperature of 3,480° F., it is necessary to have an average of about 12.5 per cent of CO_2 in the escaping gases and to burn a coal of about 14,000 B. t. u. per pound of dry coal. This temperature is about the highest that could be obtained by a hand-fired furnace. If it were possible to maintain a completeness of combustion of 100 per cent at this temperature the efficiency of the boiler (72*) would be 76 per cent, which is the highest over-all efficiency attainable. (See fig. 65.)

PLOTTING OF PROBABILITY CURVES.

After having obtained the values of furnace and true boiler efficiencies as explained on pages 143–145, the true boiler efficiencies were arranged in groups according to their values, and the number of each group was plotted according to its magnitude as shown in the upper curve of fig. 67, called the probability curve. (See p. 158.) If a line be drawn through these points a curve results quite as sym-

metrical on both sides as a probability curve and shaped very much like it.

The lower curve of fig. 67 is a similar plotting of the number of efficiency 72* values for the same tests falling within each group, the curve being drawn through the points. It lacks the symmetry of the upper curve, and the points do not fall so near the peak. The symmetry of the upper curve and its similarity to a mathematical probability curve suggest that the true boiler efficiency (E_4) is much more nearly constant than efficiency 72*, and that the attempt made to find a constant true boiler efficiency is along the right track. But the curves of fig. 66, discussed on page 143, show that this "constant" true boiler efficiency is subject to variations when capacity

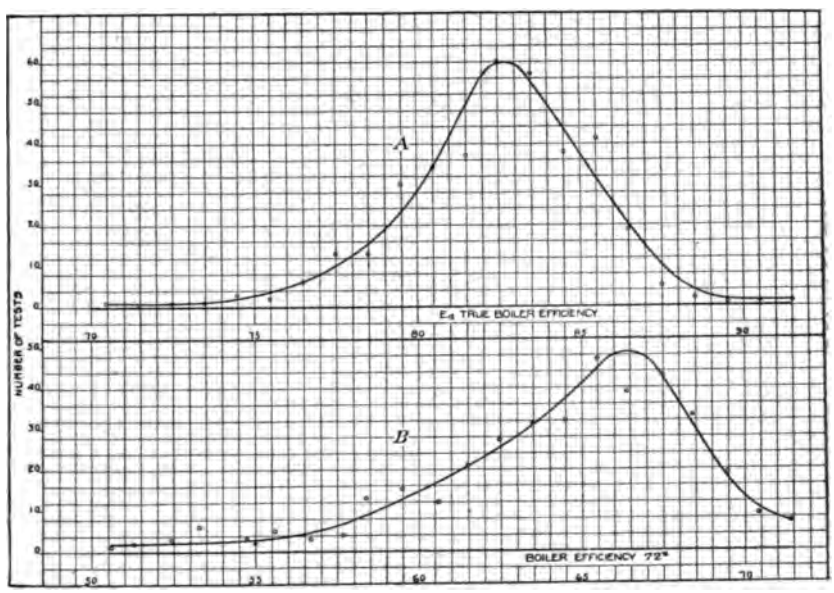

FIG. 67.—Probability curves: *A*, Approximate curve based on true boiler efficiency; *B*, attempt at approximate curve based on boiler efficiency 72*. Tests 89–401.

and furnace temperature are changed, although they are comparatively slight. By referring to the upper curve of fig. 67, it will be seen that most of the tests fall between 77 and 87 per cent, the greater number being close to 83.7 per cent, the position of the peak. This means that under average conditions the boilers at the fuel-testing plant will absorb about 83.7 per cent of the heat available to them.

The meaning of constant-capacity curves for boiler efficiency (E_5) could perhaps be made plainer by taking from the chart (fig. 65, p. 141) four specific examples:

Example 1. Taking the furnace temperature at 2,500° F., and moving from left to right on the chart, we cut lines of higher capacity and lower boiler efficiency (E_5); with a capacity increase from 70 to 120

per cent, the boiler efficiency drops from 71 to 67 per cent. Inasmuch as the furnace temperature remains constant the quantity of heat received by the lower row of tubes by conduction through the encircling tiles and by radiation from the hot brickwork is perhaps the same. Therefore the decrease in boiler efficiency must be charged to the tubes which are farther from the furnace and receive their heat from the gases by convection and conduction.

A possible explanation of lower boiler efficiencies with higher capacities is that a steeper temperature gradient is required to transmit more heat through the soot, metal, and scale. There is also a thicker layer of steam bubbles on the heating surface, which increases the resistance to the passage of heat. These effects cause the flue gases to leave the heating surface of the boiler at higher temperatures as the capacity increases.

Example 2. Using the scale at the foot of the chart and following the line of 15,000 pounds of gas passing over the heating surface per hour, we find that with a calculated furnace temperature of 2,100° F. the boiler efficiency (E_5) is about 67 per cent and the capacity about 70 per cent. Moving vertically upward the pounds of air must be slightly reduced and more coal burned in order to obtain higher furnace temperature and at the same time keep the pounds of gas per hour constant. By doing this more heat becomes available for raising the temperature of the gases, as shown by the ordinate on the right of the chart. At a furnace temperature of 3,300° F., the capacity is 130 per cent and the boiler efficiency (E_5) 75 per cent, an increase of 8 per cent over the efficiency with a temperature of 2,100° F.

Example 3. Taking the curve of 100 per cent rated capacity we find that rated capacity can be obtained with many conditions. The first extreme is with a furnace temperature of 2,100° F., when passing 21,000 pounds of gas through the boiler per hour; obtaining a boiler efficiency (E_5) of 64 per cent. The second extreme is with a furnace temperature of about 3,500° F., and a boiler efficiency of 76 per cent, when passing about 11,000 pound of gas through the boiler per hour.

Example 4. A boiler efficiency of 70 per cent can be attained under many conditions. The lowest temperature on the chart with which this efficiency can be obtained is 2,400° F. at a capacity of 70 per cent, when passing about 12,000 pounds of gas through the boiler per hour. In order to maintain this high efficiency when working at 130 per cent of rated capacity, it is necessary to increase the furnace temperature to 2,800° F. by burning more coal with decreased air supply.

The curves of fig. 66 (p. 144) differ from those of fig. 65 (p. 141) in that true boiler efficiency (E_4) is used instead of boiler efficiency (E_5). The true boiler efficiency is based on the heat available to the boiler,

considering only that part of the heat in the gases as available which is above the temperature of the steam. If the steam and water in the boiler were at atmospheric temperature, the two efficiencies, E_5 and E_4, would be the same; but as the temperature of the water in the boilers is always from 150° to 200° F. above the atmospheric temperature less heat is available for the boiler.

The general significance of the chart is (1) that true boiler efficiency increases with initial temperature, perhaps because an increasing amount of heat is absorbed by the lower row of tubes on account of conduction through the encircling tiles and of radiation on them, where they are bare in the rear, from the brickwork of the combustion chamber, and also because the higher temperature of the gases causes a steeper temperature gradient through the soot, metal, and scale, so as to cause a higher rate of flow of heat. All these causes are apart from the simplest statement of Perry's suggested theory of constant true boiler efficiency and are modifying factors of it in practice. The further general significance of this chart is (2) that at the same initial temperature the true boiler efficiency decreases as the mass of gases passed over the heating surface increases—that is, as the capacity increases. The explanation of the fact that the true boiler efficiency (E_4) is lower with these conditions is that inasmuch as capacity is proportional to the rate of heat absorption by the boiler the temperature difference between the water in the boiler and the first layer of gases on the outside must be greater in order that more heat be transmitted into the water in the same length of time. This increase in the temperature gradient causes the gases to leave the heating surface of the boiler at a higher temperature than in the cases of low capacity. The efficiency range of this chart is not very large—only from 77 to 85 per cent—and few points are near the extremes.

MISCELLANEOUS.

RELIABILITY OF OBSERVATIONS AND DATA.

The following remarks are given to facilitate the utilization of the actual data of the tests which are discussed in this volume:

Item 2: Duration of trial. This item is important for its effect on the water level in the boiler, which is easily changed several inches by opening or closing the steam valve, or by starting or stopping a large engine. Perhaps the usual error on this account was a fraction of 1 per cent of the evaporation. The item also enters into the errors of estimating the amount of fuel on the grate at starting and stopping. This estimating was always done with care, but the error on ten-hour tests may have been sometimes as much as 1 per cent of the coal burned, especially if the amount was small. As regards the fuel, when estimating accuracy, the real question is, How much coal was burned? not, How long did the test last?

Item 3: Grate surface, square feet. Boiler No. 1 was equipped with a plain grate, having an area of 40.55 square feet. Boiler No. 2 was equipped with a McClave rock-

ing grate, having an area of 36.4 square feet. These areas were maintained constant during the 1905 tests.

Item 11: Barometer, inches of mercury. This observation was always obtained from the Weather Bureau, and no correction was made for difference in elevation between the Weather Bureau station and the fuel-testing plant, which was only a few feet.

Item 11.1: Steam pressure. This reading was sometimes taken from a calibrated steam gage and sometimes from a recording-instrument chart. It is correct within a pound.

Items 12 and 13: Draft readings. These readings are accurate to 0.02 inch.

Item 16: Temperature of fireroom. Correct within 2°.

Item 17: Temperature of steam, calculated.

Item 18: Correct unless otherwise noted.

Item 20: Correct unless otherwise noted.

Item 21: Generally low, owing to air leakage, and apt to be in error in extreme instances, as much as 100° F., this error being the aggregate of the thermometer error and the greater error due to the difficulty of obtaining a true average temperature in the stack by the use of a single thermometer. Large errors are noted in their respective tests.

Item 21.1: Average temperature of furnace. Read by means of a Wanner optical pyrometer. All observations were made looking into the combustion chamber, about 2 feet from the rear end, 1 foot below the tile roof. When looking at flame, as was generally the case, the indications were perhaps well within 200° F. of the right value, generally perhaps within 100° F., although this is merely an estimate based on circumstantial evidence. In the absence of flame, light was received from the opposite wall, which was plainly cooler than the gases, as was evident on comparing it by eye with the tile roof near by; and even this latter was cooler than the gases which heated it, because heat was constantly passing upward through the tile into the water tubes. How much too low such readings are is only a guess—perhaps 100° to 200° F. In general, the tests on coals high in "fixed carbon" have combustion-chamber temperatures too low.

Item 28: Total weight of ash and refuse. Refuse was taken to mean everything which fell through the grate plus the ash and clinker pulled out of the furnace during cleaning of fire. It is noteworthy that the weight of earthy matter in the refuse from a test is usually 15 or 20 per cent short of the amount that the chemical analysis indicates; the difference undoubtedly goes over into the combustion chamber and up the stack.

Item 32: Fixed carbon of proximate analysis.

Item 33: Volatile matter of proximate analysis.

The preceding two items are based on arbitrary methods of driving off the so-called "volatile matter" and weighing the remainder to get ash and fixed carbon. By varying the standard of conditions under which the distillation is effected very different results can be obtained, and thus it may be seen that care should be exercised in deducing results of practical trials from the purely arbitrary results obtained from proximate analyses of dry or moist coal. A greater number of ultimate analyses should customarily be made, inasmuch as they furnish absolute data. Coal molecules are probably complex, and although little is known on the subject it is likely that the products and even the amounts of products of destructive distillation vary widely with the method followed, as to temperature, rapidity of heating, etc.

Item 34: Percentage of moisture in coal. This item is uncertain at best. It is probable that on warm, dry, and windy days the coal lost some moisture while being quartered on the floor of the boiler room, so that the coal fired was really lower in heating value than the chemical analysis indicates.

Items 37, 38, 39, 40, 41, and 42: Ultimate analysis of dry coal. Furnished by the chemical division.

Items 50 and 51: Furnished by the chemical division. These items were used in test calculations in preference to items 52 and 53.

Items 54 and 56: These items are untrustworthy in these tests; concordant results were never obtained. All the investigational work done on the matter pointed to the possibility that eddies vitiated the readings, because the vertical section of pipe in which the sampling nipples were placed was only 2 feet long. These items are probably not reliable within 50 per cent of the values given.

Item 77: Percentage of smoke. Dense black (so estimated) taken as 100 per cent.

Item 81: Average thickness of fire. Only approximate, because of difficulties of measurement when flame is present. It also varies with the personal equation of the observer.

Items 84, 85, 86, 87, and 88: These items are somewhat in error, owing to air dilution.

Heat balance: Items 2 and 3, very nearly correct; item 4, usually doubtful, owing to inaccurate flue-gas temperatures; item 5, only approximate; item 6, doubtful—results of our tests show that the unaccounted-for loss and the flue-gas loss up the stack take and give reciprocally. (See fig. 35, p. 63.)

The chart shown in fig. 68 indicates that in general terms the unaccounted-for heat increases in percentage with the loss due to CO.

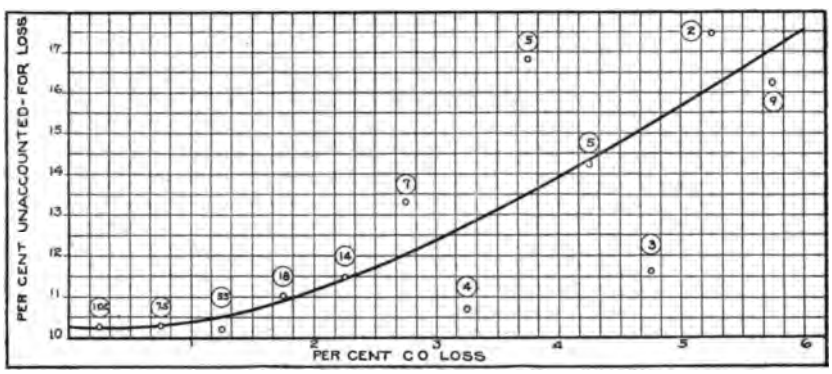

FIG. 68.—Relation of unaccounted-for loss to CO loss (tests grouped on basis of per cent of CO loss).

COMPUTATIONS OF A STEAMING TEST.

The data necessary for complete results of a steaming test come from three sources: (1) The boiler room, (2) the chemical laboratory, and (3) the United States Weather Bureau.

After a coal has been tested, from ten days to two weeks are required for the chemical work to be completed before definite results are known. The state of weather, the barometric pressure, and the relative humidity for the day of the test are obtained from the Weather Bureau.

The computed results given in this report have been calculated according to the methods indicated in the A. S. M. E. code for making boiler trials. However, it has been thought advisable to explain how several of the items were obtained or determined, and in doing this, for brevity, code numbers will be used.

Item 23: See explanation under "Average diameter of coal," p. 45.

Item 27=item 25×(100−item 34).

Item 28=total ash and refuse from test. This includes the coal which falls through the grate.

Item 29: In most tests the ash which was pulled from the grate when cleaning fires was called clinker unless the ash which formed on the grate was all free ash. Then the per cent of clinker is this weight figured as a percentage of item 28.

Item 30=item 27−item 28.

Item 30*=item 25×(item 32+item 33)−(item 28×item 44).

Item 31=item 28÷item 27.

Item 32a=item 32÷(item 32+item 33).

Item 33a=item 33÷(item 32+item 33).

Items 37a, 38a, 39a, 40a, 41a are determined by dividing items 37, 38, 39, 40, and 41 by (100−item 42).

Item 46=item 27÷item 2.

Item 47=item 30÷item 2.

Item 47*=item 30*÷item 2.

Item 48=item 46÷item 3.

Item 49=item 47÷(item 7=2,031).

Item 49*=item 47*÷(item 7=2,031).

Item 51=item 50÷(100−item 42).

Item 54, obtained by separating calorimeter.

Item 56, "quality of steam," found by subtracting item 54 from 100. In boiler use this value must be corrected, and it is the corrected value that we have used for this item.

Extract from the A. S. M. E. code for making boiler trials: "The factor of correction for quality of steam in a boiler test differs from the quality itself from the fact that the temperature of the feed water is lower than that of steam." In using quality of steam, as given by the calorimeter, therefore we lose the heat required to raise the temperature of the moisture in steam to steam temperature. The method of determining the factor of correction for quality of steam is given below:

Q=quality of moist steam as given by calorimeter.

P=the proportion of moisture in steam.

F=the factor of correction for the quality of the steam when the steam is moist.

H=the total heat of the steam due to the steam pressure.

T_1=the total heat in the water at the temperature due to the steam pressure.

J_1=the total heat in the feed water due to the temperature.

$$F=\frac{Q\,(H-J_1)+P\,(T_1-J_1)}{H-J_1}=Q+P\left(\frac{T_1-J_1}{H-J_1}\right)$$

Item 57: This is corrected for inequality of water level and of steam pressure at beginning and end of test.

Item 60$=\frac{H-h}{965.7}$, in which H and h are, respectively, the total heat in steam of the average observed pressure, and in water of the average observed temperature of the feed. The difference between H and h gives the heat absorbed. The 965.7 is the heat of vaporization at 212° F. Dividing H−h by 965.7, we obtain a factor which we can use as a multiplier to reduce pounds of water fed to boiler to pounds of equivalent water.

Item 61=item 57×item 56×item 60.

Item 65=item 63÷34.5 (34.5 pounds water evaporated per hour into dry steam from and at 212°, equals 1 boiler horsepower).

Item 68=item 57÷item 25.

Item 69=item 61÷item 25.

Item 70=item 61÷item 27.

Item 71=item 61÷item 30.

Item 71*=item 61÷item 30*.

Item 72=item 71×965.7÷item 51. This is the efficiency of the furnace and boiler *combined*, figured from pounds of combustible apparently ascending from the grate.

Item 72*=item 71*×965.7÷item 51. This is the efficiency of the furnace and boiler combined, figured from pounds of combustible actually ascending from the grate.

Item 73=item 70×965.7÷item 50. This is the efficiency of the furnace, boiler, and grate. It is usually styled over-all efficiency.

Item 77: Smoke readings were taken by using the Ringelmann charts. To obtain this item the sum of the readings was multiplied by 20 and this result divided by the total number of readings.

Item 81: Estimated by expert in charge of fire.

Item 82: The fire was considered to be in normal condition from the start of the test until the close, except during cleanings. The time for cleaning is subtracted from the length of the test and the result divided by the number of firings.

Item 83: This is the interval between raking, slicing, and cleaning the fire.

The following items are from the heat balance or distribution of the heating value of the combustible:

Total heat value of 1 pound of "combustible," B. t. u.—item 51.

Item 1=item 71*×965.7 (evaporation from and at 212° F. per pound of "combustible" ascending from the grate×965.7).

Item 2=item 34÷(item 32+item 33)÷100×[(212−t)+965.7+0.48 (T−212)]. This operation consists in referring the moisture to "combustible," raising the temperature to 212° F., evaporating it, and then superheating to stack temperature. The specific heat of superheated steam was taken as 0.48. t=temperature of air in the boiler room, T=temperature of the flue gases.

Item 3=item 38a÷100×9×[(212−t)+965.7+0.48 (T−212)]. This operation assumes all the hydrogen burned to water. The temperature of the water is raised to 212° F. and the water is evaporated and then superheated to stack temperature.

$$\text{Item } 4=\frac{11\times\text{item } 84+8\times\text{item } 85+7\ (\text{item } 86+\text{item } 88)}{3\ (\text{item } 84+\text{item } 86)}\times\frac{\text{item } 37a}{100}\times 0.24\times(T-t),$$

t=temperature of air in boiler room; T=temperature of the flue gases. The above operation consists in figuring the pounds of dry chimney gases per pound of carbon; this value, multiplied by the per cent of total carbon in the combustible, gives pounds of dry chimney gas per pound of combustible; this number of pounds of gas is then heated from the temperature of inside air to stack temperature at a constant specific heat of 0.24.

$$\text{Item } 5=\text{item } 86\div(\text{item } 84+\text{item } 86)\times\frac{\text{item } 37a}{100}\times 10{,}150.$$ The quantity 10,150 is the number of B. t. u. generated by burning to carbonic acid 1 pound of carbon contained in carbonic oxide.

Item 6=100−(items 1+2+3+4+5).

DISSOCIATION CURVES OF CARBON DIOXIDE AND WATER VAPOR.

The curves of fig. 69 are probably self-explanatory. It should be stated that the data were experimentally obtained and calculated in 1905 or 1906 by Professors Nernst and Wartenberg, two men of the highest competency. As an example, using curve No. 1, 0.051 per cent of water vapor (about 0.05 per cent) at atmospheric pressure is dissociated into hydrogen and oxygen. These data are probably the most reliable extant. They indicate that many fears heretofore widely held, as to limitations in high-temperature work due to dissociation, are almost groundless.

It will be noticed that the per cent dissociation of CO_2 increases more sharply at about 1,300° C. than anywhere else. On referring to fig. 14 (p. 23), giving the percentage of CO as a function of com-

bustion-chamber temperature, it will be noticed that the sharpest curvature of the CO curve is at about 2,600° F. (about 1,420° C.), which is not far from 1,300° C.

Now comes in the vital factor of furnace practice. In order to get higher temperatures the air supply must be reduced; and less

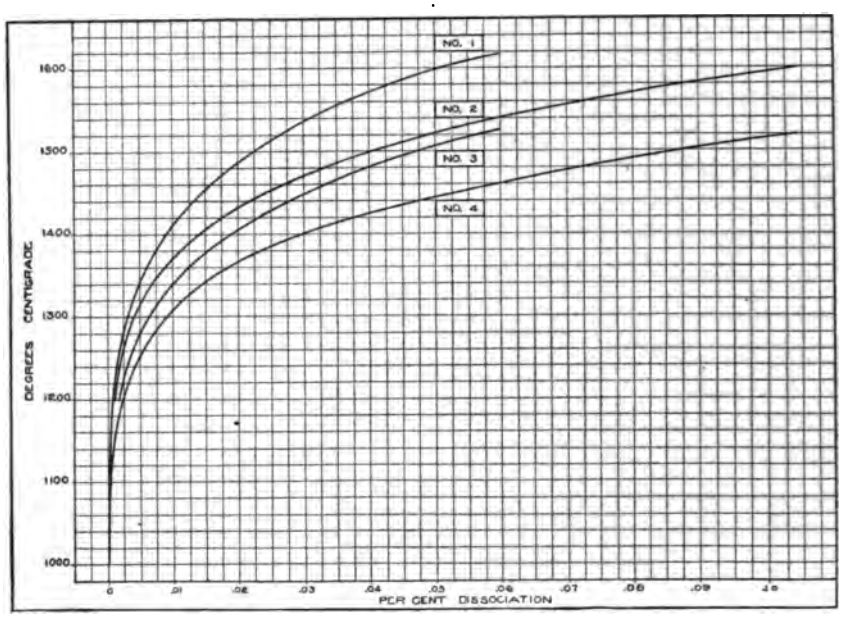

FIG. 69.—Dissociation curves of water vapor and carbon dioxide: Curve No. 1, H_2O at atmospheric pressure; No. 2, CO_2 at atmospheric pressure; No. 3, H_2O at 0.1 atmospheric pressure; No. 4, CO_2 at 0.1 atmospheric pressure. Data from Zeitschrift für physikalische Chemie, vol. 56, No. 5, 1906.

oxygen means poorer combustion, as discussed under "Mass action" (p. 170). Thus high temperatures are associated with incompleteness of combustion, shown in figs. 14 (p. 23) and 31 (p. 51).

WATER-JACKETED GAS SAMPLER.

Fig. 15 (p. 24) shows a water-jacketed gas sampler, consisting of a 1¼-inch pipe closed at each end with a cap and two ¼-inch pipes. The gas is drawn through one of the ¼-inch pipes, which passes through both the caps as indicated in the figure. The other ¼-inch pipe brings cold water into the large pipe. The ¼-inch nipple, fitted into the same end of the large pipe as that at which the water enters, serves as a water outlet. The water used for cooling the sampler is obtained from the city mains. The only difficulty ever experienced in the use of the sampler was when the city pressure was suddenly reduced.

Probably the gas drawn through this sampler would be more truly representative of the actual composition of the hot gases in the furnace if the opening from the furnace into the water-jacketed

passage were smaller. The internal diameter of a ¼-inch pipe is about three-eighths of an inch. Probably it would be better to use a brass pipe of very small bore, say ⅛-inch. The object of having the gases enter a small-bore pipe would be to cool them suddenly so as to permit no combustion while they were being cooled. Still it is not likely that any serious error is introduced by using pipe of ⅜-inch bore.

COMPARISON OF READINGS OF CERTAIN GAS SAMPLERS.

Fig. 70 shows the results of using simultaneously the code "multitubular sampler" at the base of the stack and a single small pipe a few inches above it, reaching across the stack base, and perforated

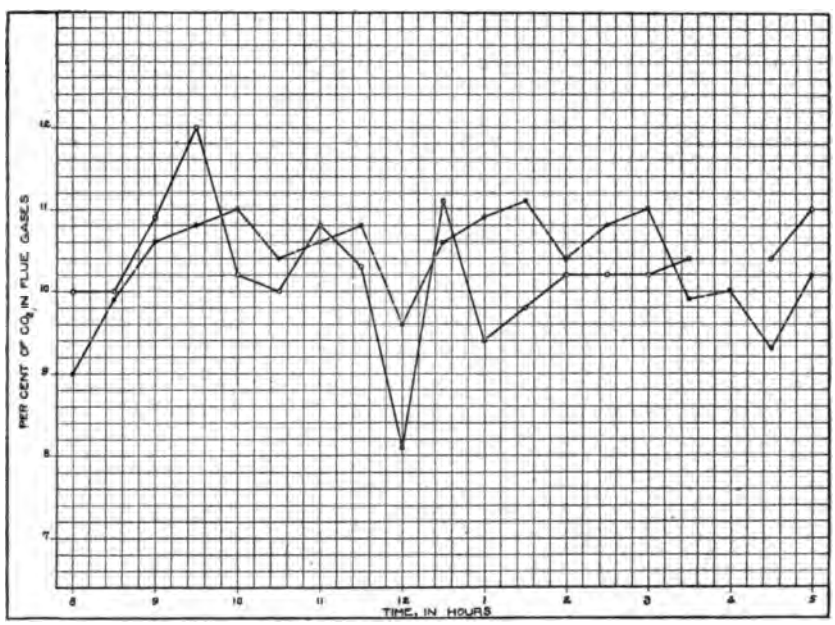

FIG. 70.—Comparison of readings of multitubular gas sampler (broken line) and of single tube in stack (solid line); test 168.

with several small holes at intervals. It will be noticed that the multitubular sampler gave a more even line, on account of its containing a large storage space; the daily average for the two was the same within 0.1 per cent. But this excellent showing with the multitubular sampler was obtained only by constant care of it, for it gave a great deal of trouble from leakage.

The current of gas through the small sampling tubes is too slow, so that the soot and small particles of ash settle in them and harden, thus gradually stopping the openings. Tubes used in sampling from streams of gas carrying the most soot and ash become stopped sooner than others. Thus the multitubular sampler loses the apparent advantage, which led to its design, of drawing a sample from

every portion of cross section of the gas passage, and thereby loses also its value as a flue-gas sampler. It may be stated here that when the sampler was taken out, after two years of usage, about three-fourths of the sampling tubes were found to be stopped up, although the sampler had been often blown out with steam. Its worst disadvantage lay in its leveling all readings considerably, so that the man running the fire could not depend on it for guidance so much as the single-tube sampler. For these reasons the A. S. M. E. multitubular sampler was permanently discarded.

The above-described faults of the multitubular sampler would not be so serious when using coals high in "fixed carbon."

FLUE-GAS SAMPLER.

Fig. 71 shows a design of a different form of flue-gas sampler which has been installed at the fuel-testing plant. The purpose of this design of collector is to obtain gas from various portions of the stack and mix it before its temperature is taken and a sample drawn for analysis. This sampler is built of No. 16 sheet iron, and consists of a cylinder 5 inches in diameter to which are connected, by means of a double cone-shaped body, six scoops making an angle of 45° with the axis of the cylinder. The area of the cross section of these scoops is 2.25 by 3 inches. In the bottom of each of the scoops is an opening which diminishes in width toward the center of the sampler, making the opening proportional at all points to the respective distances of the points from the center. The openings are shown in the bottom view of the sampler (fig. 71). The sampler is placed in the round portion of the stack about 2 feet below the damper, the ends of the scoops being about 4 inches above the top of the hood. The largest diameter across the scoops is about 6 inches smaller than the diameter of the stack.

The sample of gas is drawn through a ¼-inch pipe, the end of which is inserted to the center of the 5-inch cylinder, as shown. The bulb of a flue-gas thermometer is also placed at the center of the cylinder near the ¼-inch pipe, so that the temperature of the flue gas and the sample of gas for analysis are taken at the same place. It is very probable that by this design of the sampler and location of the thermometer and sampling tube the average temperature and composition of the flue gas are obtained. To prevent the cooling of the gases by radiation after they have left the heating surface of the boiler the base of the stack was covered with asbestos. On close examination at the end of five months' constant use this sampler was found in perfect order in every respect and free from soot, both inside and out.

UNACCOUNTED-FOR PERCENTAGES PROBABLY TOO HIGH.

Of late years the opinion has been gaining ground that all gases increase in specific heat as their temperatures are raised. If this is

true, more heat is lost up the flue than has been calculated on the basis that the specific heats of dry flue gases and steam were respectively constant at 0.24 and 0.48 under constant pressure.

If we assume, for instance, that the data given in E. Damour's Industrial Furnaces are correct, at an average flue temperature of 662° F. (350° C.) the true amount of heat lost up the flue was roughly

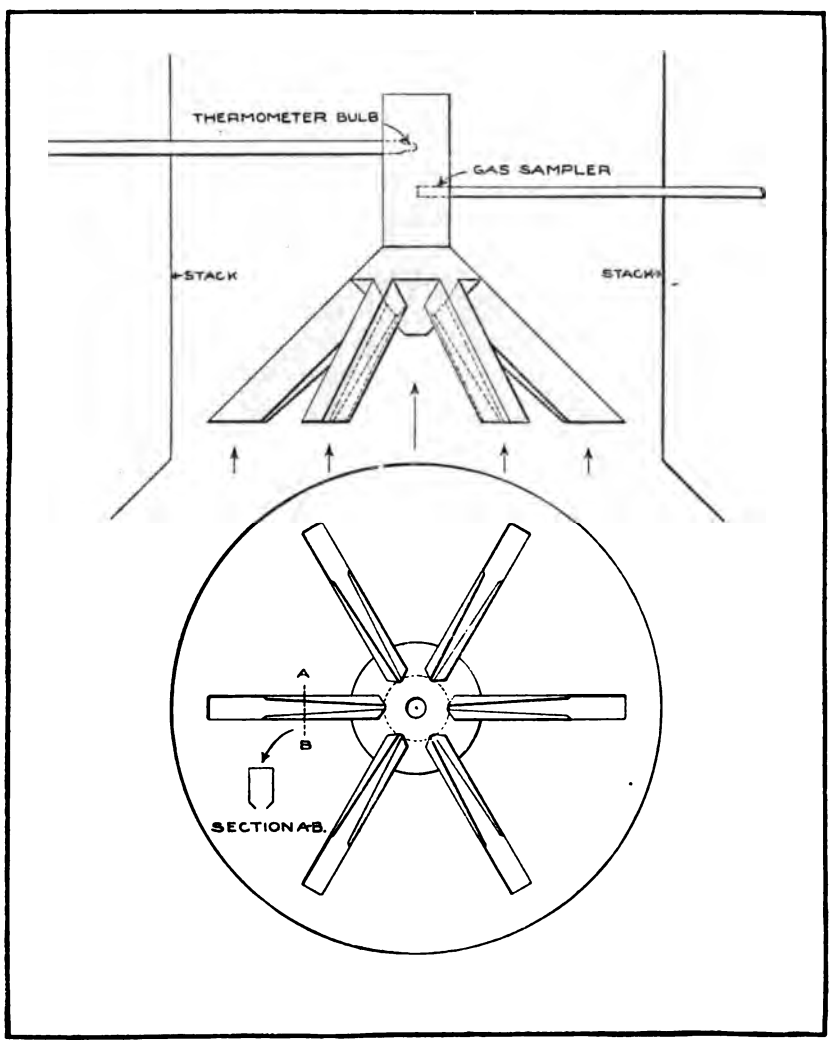

FIG. 71.—Flue-gas sampler installed to replace A. S. M. E. multitubular sampler.

5 per cent more than the amount regularly calculated—about 1 per cent of the heating value of the fuel. This loss would be subtracted directly from the unaccounted-for heat; for instance, if the latter is given as 15 per cent it may really be about 14 per cent. But in consideration of the fact that in the last few years little work has been

done by physicists on the specific heats of gases at high temperatures the values given by Damour are probably not final, and so the calculations here given are subject to withdrawal.

PROBABILITY CURVES.

It is stated on pages 132 and 146 that when the calculated values of certain "constants" sought for are plotted according to the number of constants falling in each narrow group the free-hand curve drawn through the points resembles a probability curve, and the peak is at a certain value of the constant. This relation makes it probable that the true value of the constant is the peak value, especially if the curve is narrow and symmetrical on the two sides and if the arithmetical average of all the points falls close to the peak of the curve. Perhaps the explanation can be best stated by reference to fig. 72.

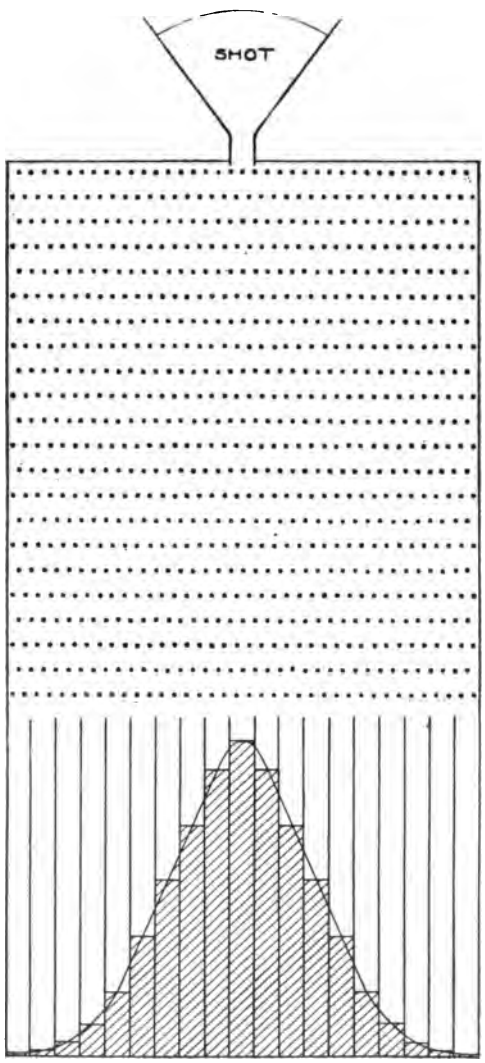

FIG. 72.—Diagram illustrating probability curve.

When shot are dropped into the funnel they ought to fall into a vertical column the width of the funnel, but they will actually spread out, owing to obstructions. The curve drawn through the tops of the piles is a probability curve.

If a man were measuring a length carefully (as with a tape or with a micrometer), while very few of his readings would coincide if a large number of readings were used, the arithmetical average would be closely correct.

If all his readings were sorted according to lengths as read and plotted with the vertical ordinate as the number of readings falling in each group and the horizontal ordinate as the average length of the readings in the groups a curve would result much like a probability curve. But

suppose it was questionable whether or not the measured object changed length in unknown ways, if many measurements were taken the width of the curve would give a clew as to whether or not there really was any constant length. If a large number of readings formed a curve close to a theoretical probability curve the presumption of constant length would be nearly justifiable.

Perhaps the best treatment of this subject for engineers is in J. W. Mellor's Higher Mathematics for Students of Chemistry and Physics, a very helpful book to the chemical engineer.

The equation to this curve is

$$y = ke^{-h^2x^2}$$

in which y = height of vertical ordinate at any point.

x = horizontal distance of any point on the curve from the center line passing up and down through the peak.

e = base of hyperbolic system of logarithms, = 2.7183.

h = a constant for each curve, which determines its width; the larger h the narrower the curve, and hence the more reliable as an indicator of the probable value sought.

k = a constant for each curve, determining its height.

The boiler division has plotted a number of curves of this equation, one or another of which is used to fit over any curve to which it bears a strong resemblance. But even if the fit is perfect no more is proved than that there is a strong probability that the figure sought is constant at the peak value. However, even this use of the equation and curves will serve to indicate whether a guess is along the right path, and in this way their use is sure to increase when they are generally known among engineers.

RELATION OF TEMPERATURE OF PRODUCTS OF COMBUSTION TO POUNDS OF AIR USED.

Fig. 73 was prepared as a graphic illustration to show the different comparative temperature elevations attainable by completely burning various fuels, on the assumption that the specific heats of gases at constant pressure do not change with increase of temperature. It was thought that this assumption was wrong, but in the absence of more definite values it was decided to use constants. The general effect of this assumption is probably to make the temperatures with small air excesses too high; thus all the curves are somewhat too steep. In calculating the temperature the specific and latent heat of moisture in fuel and moisture formed by combustion have been considered.

The main object of the chart is to show that some Illinois coals are capable of use in high-temperature work, as in making malleable-iron castings. In fact, by preheating the air used for combustion, Illinois coals are now burned in reverberatory furnaces in Chicago

and St. Louis. The curve shows that lignites could be used with preheating, especially as some lignites are very low in sulphur and burn freely with a long, hot flame.

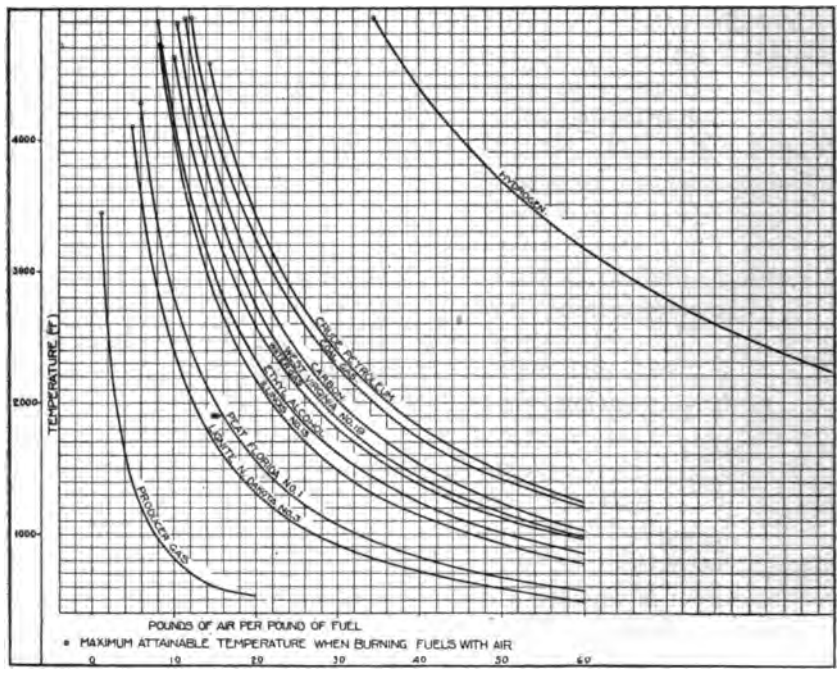

FIG. 73.—Theoretical curves showing relation of temperature of products of combustion to pounds of air used per pound of various fuels.

CIRCULATION INDICATOR.

The construction of the circulation indicator is shown in fig. 74, which is a view of the instrument as mounted in the boiler. There are six essential parts which go to make up the indicator, as follows: The wheel or propeller, the contact strip, the brush that rests on it, the shaft, the supports or bearings of the shaft, and the receiving instrument (which may be a telephone).

The wheel is made up of four copper blades, secured to spokes by copper rivets and set at an angle of 30° with the axis of the shaft. The spokes are attached to a piece of brass tubing that acts as a hub and also as a support for the contact strip.

The contact strip is mounted on an insulating drum consisting of a glass tube about 1½ inches long slipped on the brass hub, which it fits tightly. A strip of copper about one-eighth inch wide and one thirty-second inch thick is bound to the glass tube with copper wire, and is electrically connected to the hub of the wheel by a copper-wire bond.

The brush is a piece of watch spring, supported on a copper bar that is insulated from the remainder of the instrument by mica washers. It is arranged at right angles to the contact strip, with its end resting lightly thereon so as to make and break contact with the copper strip once every revolution of the wheel. A copper wire, that connects to a telephone receiver on the outside of the boiler through a 2-volt battery, is bonded to the brush support and insulated by means of rubber tubing at the point where it passes out of the boiler between the hand-hole cover and the water leg. The other wire from the telephone receiver is grounded to the boiler, as shown. By using a low voltage on the line the current is not short circuited much through the water in the boiler.

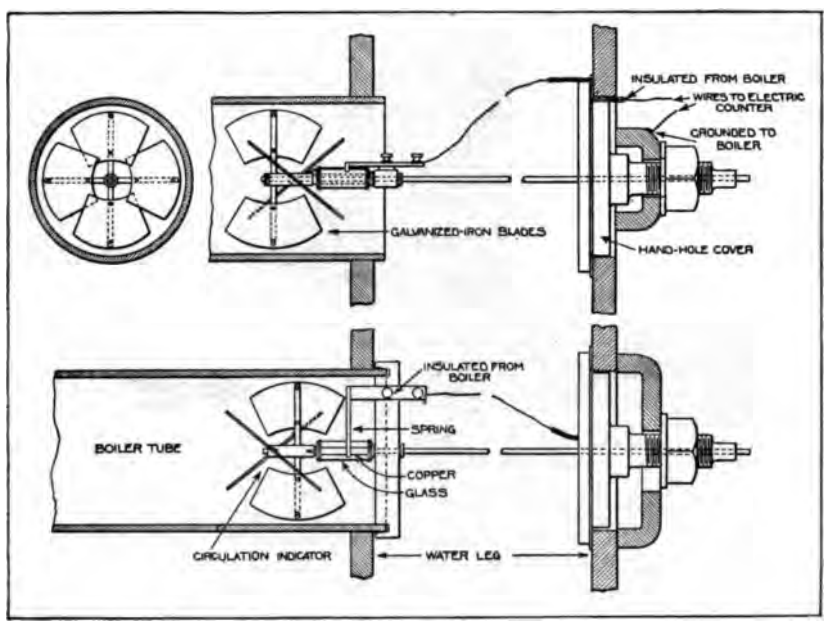

FIG. 74.—Circulation indicator mounted in boiler.

The shaft on which this instrument turns is a piece of brass wire about one-eighth inch in diameter and about 16 inches long. Two collars attached to the shaft close to the wheel, one on each side of the support, serve to keep the shaft from moving back and forth, and one of them, in conjunction with a cotter pin in the end of the shaft, holds the propeller in place.

One support for the shaft, at the end nearest the wheel, is a bar of brass with a hole in the center for the shaft and a slot on each end. These slots, which engage on the outside edge of the boiler tube, as shown, facilitate the centering of the instrument and changing from one tube to another. The other support for the shaft was

obtained by drilling a hole through the center of a hand-hole cover and adding a small stuffing box made from the gland of a valve.

In the operation of this instrument the flow of water in any tube of the boiler in which the circulation indicator might be placed causes the wheel to rotate at a rate of speed proportional to the rate of flow. By placing the receiver to the ear a click is heard for each revolution, and one revolution of the indicator means the passage of approximately 1 foot of water. As the speed of rotation in all trials up to date has not been too high for an observer to count the clicks, no difficulty was encountered in keeping a record of the rate of flow in any boiler tube under observation under varying conditions of operation of the boiler.

Several instruments were built and tried before success was attained with this one. The instrument has lately been used to work an automatic counter through a couple of telegraph relays.

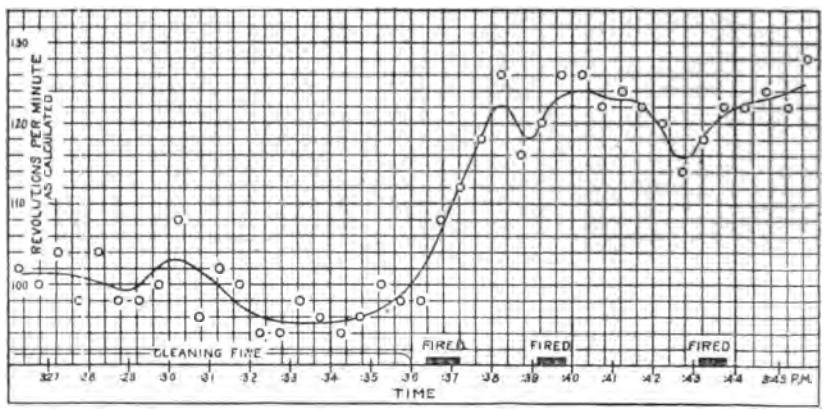

Fig. 75. Result of observations with circulation counter (propeller in back of boiler, middle tube, third row from bottom); test 379. Revolutions per minute calculated from averages of two readings of revolutions per fifteen seconds.

For information obtained see figs. 7 (p. 16) and 75 and pages 163 and 164.

Fig. 75 shows the effect of cleaning fires, and of firing, on the speed of water circulation in a tube of the boiler, as measured relatively by the circulation indicator illustrated in fig. 74 and described on pages 160-2. The circulation is prompt in its changes and the values obtained vary considerably. The readings were taken by recording the number of revolutions in a fifteen-second interval opposite time figures, and from such data the temporary rate in revolutions per minute was calculated and plotted on this chart.

The curves of fig. 7 (p. 16) are based on readings taken for several days with the circulation indicator. The data from which the two curves were plotted were obtained by counting the total number of

revolutions of the indicator for each half-hourly period, and by calculating the percentage of builder's rated horsepower of boiler developed for each such period, respectively. The small circles give the positions of points and the numbers in the large circles near by give the number of half-hours fulfilling the coordinate values of the points. After plotting, the points were averaged in value in both horizontal and vertical strips, each point being included for averaging as many times as indicated by the number in the circle near by. Thus the two curves were determined. It will be noticed that they are very close together, indicating the reliability of the method of working up the data.

The important point is that the circulation rapidly drops behind the amount of steam made (per cent of rated capacity developed), especially at high rates of working. Thus at 70 per cent of rated capacity the average speed of rotation of the indicator was 80 revolutions per minute. At 105 per cent of rated capacity the rate of revolution was 102, whereas to be proportional it should have been 120; the speed of circulation fell about 15 per cent short.

This result is reasonable when we consider that, so far as one can make any speculations, the circulating forces are perhaps roughly proportional to the amount of steam which is generated and entrained with the rising water, whereas the frictional resistance to circulation is perhaps proportional to the square of the average velocity of circulation.

This failure of circulation to keep up proportionally with demands on it must decrease the efficiency of the boiler at higher rates of working, by allowing a proportionally larger percentage of the water-heating surface to be covered with steam bubbles, thus virtually reducing the heating surface. That this condition does supervene is indicated on a number of charts, for instance those shown in figs. 5 (p. 14) and 8 (p. 17), which should be noted in this connection.

At a later date the circulation indicator was put in the middle tube of the lowest row of tubes, this being one of the tubes inclosed in clay tiles except at the rear end. The revolutions per minute for various capacities are given in the following table:

Readings of circulation indicator showing revolutions per minute for various capacities.

	Capacity.			
	58.2.	91.4.	118.2.	92.2.
Number of readings	78	8	7	12
Revolutions per minute	217	257	273	291

The number of revolutions at any capacity is approximately three times as great as the number shown in fig. 7 for the second row of tubes just above.

In an earlier experiment the same circulation indicator was placed in the third row of tubes from the top of the boiler, and it was found that the rate of revolution was very slow indeed. This result indicates that the bottom row of tubes is doing far more work than any other row, and that as we go from the bottom row up the amount of work done decreases very rapidly.

The probability that the bottom row of tubes absorbs so large a portion of the total heat, absorbed mostly on account of conduction through the clay tiles and radiation to the exposed portion of the tubes in the rear over the hot brickwork, makes it easy to realize that the efficiency of the boiler as a heat absorber may well rise far more rapidly with increasing furnace temperature than is indicated by the equation for heat absorption from the gases due to convection only, as developed on pages 129 and 130.

C-SHAPED v. FLAT-BOTTOMED TUBE TILES.

In boilers of the Heine furnace type the bottom row of tubes is incased in clay tiles. Such an installation is advantageous when coals break down, evolving gases difficult to burn, for the clay tiles serve a far better cause in protecting the burning gases from sudden cooling, and in acting as a small heat reservoir, than in protecting the tubes from burning.

The first tiles used by the testing plant were of a C shape inside and out, and although they were made of excellent material they were so easily damaged by fire tools, and cracked so often from sudden temperature changes, that a new set had to be put in every two or three months. Later, both boilers were fitted with tiles which are flat on the bottom, giving the furnace roof the appearance of a ceiling. They are only 15 per cent heavier than the old C tiles, and could easily be made as light as the old tiles by cutting off the upper outside corners, above the tubes. The new tiles have withstood hot fires for over a year and are still good. They are among the most satisfactory parts of the boiler equipment. The difficulty referred to has been experienced at several power houses, and overcome in the same way, with equal satisfaction.

ORSAT TOTALS.

The sum of the percentages of CO_2, O_2, and CO of an Orsat gas analysis is not at all constant. The sum is usually low at the start of a test and gradually rises during the first two hours. It also varies from day to day and from coal to coal. The first explanation suggested was that the available hydrogen of the coal burned to water that condensed before the gas sample arrived at the Orsat measuring tube, so that out of every hundred volumes of air which *entered* the furnace one or two volumes might well be missing in the

Orsat measuring tube. On this assumption, when the same quantity of air is used to burn various fuels those highest in available hydrogen should give the lowest totals of Orsat analyses. To test this reasoning, a tabulation was made, headed "Classification of average flue-gas totals on basis of per cent of available hydrogen in dry coal." Many tests were grouped, first according to pounds of dry chimney gases per pound of "combustible." The tests of each of these groups were then reclassified according to per cent of available hydrogen in dry coal. For each subgroup the average was found for the Orsat totals of CO_2, O_2, and CO. A glance along the horizontal rows of flue-gas totals shows but little relation between available hydrogen and flue-gas totals. This failure to connect per cent of available hydrogen with shortage in Orsat totals suggests that other causes may be at work.

Perhaps the occurrence of low totals in the first part of a test is due to the fact that an oxygen molecule may combine with carbon and form two CO molecules, which will occupy twice the space, thereby making the Orsat totals higher. During the first part of a test the CO is low, and later it rises. CO and available hydrogen have opposite effects on the totals. So it is, after all, not to be expected that either taken alone will show anything. More work will be done on this problem.

Classification of average flue-gas totals on basis of per cent of available hydrogen in dry coal.

	Per cent of available hydrogen in dry coal.									
	Under 3.	3 to 3.2.[a]	[a] 3.4 to 3.6.	3.6 to 3.8.	3.8 to 4.0.	4.0 to 4.2.	4.2 to 4.4.	4.4 to 4.6.	4.6 to 4.8.	4.8 to 5.
Less than 18 pounds of dry chimney gases per pound of combustible:										
Number of tests	2	.....	.....	1	2	8	8	5	3	.....
Average per cent of available hydrogen in dry coal	2.48	.....	.....	3.66	3.86	4.05	4.29	4.56	4.61	.....
Average of flue-gas totals (CO_2+O_2+CO)	19.33	.....	.....	19.38	18.55	19.16	18.60	19.07	18.69	.....
From 18 to 19 pounds of dry chimney gases per pound of combustible:										
Number of tests	.....	.....	1	2	2	6	11	11	9	.....
Average per cent of available hydrogen in dry coal	.....	.....	3.42	3.72	3.92	4.08	4.30	4.54	4.67	.....
Average of flue-gas totals (CO_2+O_2+CO)	.....	.....	18.92	18.71	19.15	19.04	18.72	18.82	18.62	.....
From 19 to 20 pounds of dry chimney gases per pound of combustible:										
Number of tests	1	.....	2	4	7	14	8	5	5	.....
Average per cent of available hydrogen in dry coal	2.31	.....	3.50	3.71	3.88	4.07	4.30	4.52	4.68	.....
Average of flue-gas totals (CO_2+O_2+CO)	19.16	.....	19.25	19.42	19.01	19.07	18.92	19.08	19.08	.....
From 20 to 21 pounds of dry chimney gases per pound of combustible:										
Number of tests	2	.....	.....	3	2	12	11	9	5	.....
Average per cent of available hydrogen in dry coal	2.49	.....	.....	3.76	3.98	4.08	4.30	4.51	4.72	.....
Average of flue-gas totals (CO_2+O_2+CO)	19.87	.....	.....	18.91	19.79	19.48	19.23	18.89	18.98	.....

[a] No fuels in the 3.2 to 3.4 per cent class.

Classification of average flue-gas totals on basis of per cent of available hydrogen in dry coal—Continued.

	Per cent of available hydrogen in dry coal.									
	Under 3.	3 to 3.2.	3.4 to 3.6.	3.6 to 3.8.	3.8 to 4.0.	4.0 to 4.2.	4.2 to 4.4.	4.4 to 4.6.	4.6 to 4.8.	4.8 to 5.
From 21 to 22 pounds of dry chimney gases per pound of combustible:										
Number of tests	.....	.....	1	3	1	7	8	3	5	.....
Average per cent of available hydrogen in dry coal	.....	.....	3.56	3.70	3.99	4.07	4.27	4.36	4.66	.....
Average of flue-gas totals (CO_2+O_2+CO)	.....	.....	19.29	19.23	19.65	19.52	19.17	19.36	19.08	.....
From 22 to 23 pounds of dry chimney gases per pound of combustible:										
Number of tests	.....	.....	1	3	.....	5	3	8	5	1
Average per cent of available hydrogen in dry coal	.....	.....	3.49	3.69	.....	4.06	4.29	4.48	4.69	4.85
Average of flue-gas totals (CO_2+O_2+CO)	.....	.....	19.10	19.48	.....	19.82	19.19	19.17	19.22	19.20
From 23 to 24 pounds of dry chimney gases per pound of combustible:										
Number of tests	.....	.....	1	.....	1	3	5	10	2	.....
Average per cent of available hydrogen in dry coal	.....	.....	3.47	.....	3.88	4.04	4.27	4.51	4.68	.....
Average of flue-gas totals (CO_2+O_2+CO)	.....	.....	18.92	.....	19.59	20.00	19.58	19.36	19.25	.....
24 pounds or more of dry chimney gases per pound of combustible:										
Number of tests	1	1	3	3	2	6	4	7	2	4
Average per cent of available hydrogen in dry coal	2.89	3.17	3.53	3.71	3.98	4.08	4.31	4.52	4.71	4.85
Average of flue-gas totals (CO_2+O_2+CO)	18.91	20.07	19.70	19.67	19.45	19.72	19.45	19.43	18.45	19.39

PER CENT OF CO IN COMBUSTION CHAMBER.

Fig. 14 (p. 23) shows that when combustion-chamber temperatures are high, the per cent of CO in the rear of the combustion chamber is high and the totals of CO_2, O_2, and CO are low. This concurrence of high CO and low totals of Orsat analyses has often been noticed. As a converse test, the classification tabulated below was made on per cent of CO as a basis, to obtain the average of the Orsat totals. They are practically constant until the CO becomes high, when they drop at a comparatively rapid rate. This relation is of the same nature as that indicated in fig. 14 (p. 23). No explanation is given here, as several possible ones were found to be doubtful on investigation.

Classification of Orsat totals on basis of volumetric per cent of CO in combustion chamber (tests 318–382).

	Per cent of CO.										
	0 to 0.10.	0.10 to 0.20.	0.20 to 0.30.	0.30 to 0.40.	0.40 to 0.50.	0.50 to 0.60.	0.60 to 0.70.	0.70 to 0.80.	0.80 to 0.90.	0.90 to 1.00	Over 1.00.
Number of readings	82	31	38	18	17	7	9	4	5	2	7
Average of 100-(CO_2+CO+O_2)	18.5	18.4	18.5	18.5	18.5	18.5	18.3	18.9	18.2	15.1	17.4

The following table was constructed to ascertain whether such conditions of poor combustion as permitted a high percentage of CO in

the rear of the combustion chamber also conduced to smoke production. The finding is in the affirmative. See also the chart shown in fig. 33 (p. 56), based on per cent of black smoke, in which the per cent of CO rises rapidly with the per cent of smoke.

Classification of smoke production on basis of volumetric per cent of CO in combustion chamber.

	Per cent of CO.							
	0 to 0.10.	0.10 to 0.20.	0.20 to 0.30.	0.30 to 0.40.	0.40 to 0.50.	0.50 to 0.60.	0.60 to 0.90.	0.90 up.
Number of tests	9	8	4	4	4	1	1	1
Average per cent of CO in combustion chamber, volumetric	0.03	0.14	0.23	0.34	0.44	0.58	0.83	1.10
Average per cent of black smoke	13.8	19.9	21.8	18.1	26.3	38.5	40.0	39.0

POUNDS OF DRY CHIMNEY GASES PER POUND OF "COMBUSTIBLE."

The subjoined tabulation of pounds of dry chimney gases per pound of "combustible" is based on intensity of draft under stack damper and difference of draft under stack damper and draft over fire. This table was made to ascertain whether the pounds of air used could be approximated by draft readings. As there was also air leakage, which varied with the amount of draft carried, it seemed best to average out the error by using separate readings for different values of stack draft. However, such a classification seems to be so greatly influenced by rate of combustion and air leakage as to make it of little value. The table shows a small increase of pounds of dry chimney gases per pound of "combustible" as the difference of draft increases.

Classification of dry chimney gases per pound of "combustible" on basis of stack draft and difference of draft under stack damper and draft over fire.

	Stack draft.						
	Under 0.40.	0.40 to 0.425.	0.425 to 0.45.	0.45 to 0.475.	0.475 to 0.50.	0.50 to 0.525.	0.525 to 0.55.
Number of tests	18	23	12	25	23	17	14
Average difference of stack draft and draft over fire	0.25	0.29	0.32	0.32	0.34	0.35	0.37
Average pounds of dry chimney gases per pound of combustible	19.75	19.04	18.25	19.79	20.02	19.52	21.09

	Stack draft.					
	0.55 to 0.575.	0.575 to 0.60.	0.60 to 0.625.	0.625 to 0.65.	0.65 to 0.675.	0.675 up.
Number of tests	21	16	28	18	10	32
Average difference of stack draft and draft over fire	0.38	0.41	0.41	0.44	0.47	0.54
Average pounds of dry chimney gases per pound of combustible	21.18	22.08	22.16	22.92	21.86	21.91

EFFECT OF DIRECTION, VELOCITY, RELATIVE HUMIDITY, AND TEMPERATURE OF AIR ON EFFICIENCY 72*.

Inasmuch as the boilers stood in a poorly built wooden structure, near two large doors, which were always open in summer and sometimes in winter, it was thought that the cooling of the boiler room by

winds might have some appreciable tendency to lower the efficiency 72*.

With the data from about 305 tests, the problem was attacked in several ways, as given below:

1. The winds were classified in four groups,—(*a*) from the north and northeast, (*b*) from the east and southeast, (*c*) from the south and southwest, (*d*) from the west and northwest—and then all tests were classified according to the prevailing direction of the wind for that day, and the individual tests falling in each of the four wind groups were plotted by means of the two ordinates, efficiency 72* and velocity of wind in miles per hour. It was found that there was no appreciable effect on efficiency due to wind velocity. In the above-mentioned subdivisions the tests of all groups (*a*, *b*, *c*, and *d*) were arranged in subgroups according to the outside air temperatures—for instance, the tests falling under wind from the east and southeast were divided into three subgroups, in which the ranges of outside air temperature were "below 40° F.," "40° to 50° F.," and "50° to 60° F."

2. With the same four groups of wind directions (*a*, *b*, *c*, and *d*) the item 72* (so-called "boiler efficiency") was plotted in each group with the items: (*e*) velocity of wind in miles per hour, (*f*) relative humidity of outside atmosphere, (*g*) outside air temperature, and (*h*) average diameter of coal. In group 2 (*e*) the velocity of wind again had no noticeable effect. For all directions of wind excepting from the north and northeast, high relative humidity (*f*) of the outside atmosphere appeared to lower the efficiency somewhat. A rise of outside-air temperature (*g*) appeared to cause a slight rise in efficiency, but not any more than results from an equal reduction in stack temperature, so that the effect on radiation is not noticeable. The outside doors were generally closed in winter, however. The average diameter of the coal (*h*) varied only slightly, and it apparently had no influence in disguising any of the other curves (*e*, *f*, and *g*).

The general conclusion is that calculations of radiation are not likely to be appreciably in error owing to changes in weather conditions, unless it is substantiated on further investigation that the relative humidity influences the amount of heat lost by convection or else retards the combustion of coal. Efficiency 72* was used because the "unaccounted-for" item is not reliable.

RELATION OF UNACCOUNTED-FOR LOSS TO ASH PASSING OVER BRIDGE WALL.

It was thought that possibly all the coal which was blown up from the fuel bed and carried away with the gases did not burn, and that a clew to incomplete combustion might be obtained by comparing the unaccounted-for items of the heat balance with the ash lost over

the bridge wall. The opposite from the relation expected appears in the accompanying table, which shows that the greater the per cent of ash carried away the less the unaccounted-for loss—that a high percentage loss of ash does not mean a high unaccounted-for loss. As the average difference of draft under stack damper and draft over fire increases the ash lost over the bridge wall increases, as might be expected.

The following is offered as an explanation of the table: With higher draft there is an increased rate of combustion; the temperature of combustion is increased; the pounds of dry chimney gases per pound of "combustible" are decreased; a higher initial temperature and increased rate of combustion will give a higher stack temperature, and this increased temperature will increase the loss up the stack and subtract almost directly from the unaccounted-for loss; and with increased rate of combustion the per cent of radiation loss for each pound of coal burned will be less and this reduction will enter directly into the unaccounted-for loss. These factors tend to decrease the unaccounted-for loss. On the other hand, with higher rate of combustion and higher temperatures the gases are carried through the furnace faster and there is a greater amount of incomplete combustion owing to the fact that less time is taken in passing through the furnace. Moreover, as there is less excess of air and a higher temperature, the unaccounted-for loss will directly increase because hydrocarbon losses are not determined. There is necessarily a balancing of these losses and gains. The table shows their average effect only.

Three classifications showing relation between "unaccounted-for" loss and ash passing over bridge wall.

Per cent of ash lost over bridge wall, referred to combustible burned	.....	0.58	1.24	1.73	2.26	2.69	3.26	3.72	4.42	7.01
Number of tests	.....	24	26	30	28	19	18	20	25	19
Average per cent of unaccounted-for loss from heat balance	.....	9.83	11.74	11.23	11.24	9.73	9.40	10.49	9.52	8.45
Average difference of draft under stack damper and draft over fire, inch of water	.....	0.35	0.35	0.34	0.36	0.38	0.37	0.37	0.39	0.43
Average per cent of ash lost over bridge wall	0.27	0.79	1.24	1.78	2.25	2.80	3.20	3.72	4.56	5.90
Number of tests	13	26	34	29	33	20	23	14	10	9
Average per cent of unaccounted-for loss from heat balance	10.01	10.55	12.12	10.78	10.44	9.53	9.68	9.46	7.99	9.01
Average per cent of unaccounted-for loss	5.69	7.59	8.54	9.48	10.48	11.45	12.55	13.38	14.51	16.70
Number of tests	26	24	22	29	20	30	22	12	11	15
Per cent of ash lost over bridge wall, referred to combustible burned	3.81	2.80	3.10	2.64	2.51	2.88	2.83	2.81	1.73	2.16
Average per cent of ash lost over bridge wall	3.04	2.24	2.45	2.10	1.99	2.26	2.21	2.19	1.44	1.75

THE LAW OF MASS ACTION.

Although not yet very old, the law of mass action is already one of the most firmly established and useful of the laws of physical chemistry. Its operation is a matter of daily intuition in other fields; e. g., the more water one uses the easier it is to dissolve sugar, salt, etc. But only recently has the law been mathematically formulated in chemistry, and even yet it is often so hard to learn what the reactions are that one does not know which mass-action formula to use; still, the path of some reactions has been determined by finding what formula fitted the observed facts.

To take the simple case of combustion of carbon, it is an observation as old as the art of boiler practice that considerable excess of air is needed above the theoretical amount. Mathematically the situation is as follows:

As soon as some of the oxygen of the air has united with carbon or CO it is no longer available for oxidation of the remaining combustible; worse yet, the molecules formed are in the way, so that the combinations become less and less frequent. All this, of course, is on the supposition that the temperature is kept constant, so as to eliminate other variables. Now, as the above reaction proceeds the masses of oxygen and carbon, as compared with the total masses present, become less and less, whence the name, mass action; they soon become nearly zero.

The above illustration is faulty in one respect—it does not say in what terms the masses are to be measured. Elementary chemistry states that CO and O, for example, combine in just one proportion—28 parts by weight of CO (its molecular weight) and 16 parts by weight of O (its atomic weight). The molecular weight of the oxygen is not taken (it is 32, as there are ordinarily two atoms in a molecule) as the combining weight, because the molecule must first divide. Thus we should really consider 2 molecules of CO and 1 of O_2. For these reasons both combining substances must be considered according to the numbers of gram molecules present—that is, the number of grams of each present divided by its respective molecular weight. Luckily this trouble disappears when working with gases analyzed volumetrically, as with an Orsat apparatus, because the volumetric weights of gases are directly proportional to their molecular weights, as all gases at the same temperature and pressure contain the same number of molecules per unit volume. Even dissociation, either of molecules of H_2O and CO_2 or of molecules of H_2 and O_2 and N_2 into 2H, 2O, and 2N, would not trouble us, because volumes would increase proportionately. All we need to do is to substitute the volumetric percentages of O_2 and of CO or CH_4, for example, of the analysis in the equation corresponding to the particular reaction and

obtain the relative indication of the rate of combustion, assuming, of course, the same temperature and pressure in every case.

Example: An analysis of gas from the rear of a combustion chamber through a small opening in a water-jacketed gas sampler showed the two following results, the combustion-chamber temperature in each case being 2,600° F.: (1) O_2, 4 per cent; CO, 0.5 per cent. (2) O_2, 7 per cent; CO, 0.4 per cent. The rest of the volume consisted of nitrogen, water vapor, carbon dioxide, and other gases foreign to this calculation. If the formula of the reaction is $2CO + O_2 \rightleftharpoons 2CO_2$,[a] and if at 2,600° F. the dissociation of CO_2 is only about 0.01 per cent, we may say with very close accuracy that the reaction is not a balanced one, but proceeds to a finish. It can be then written $2CO + O_2 = 2CO_2$.

If the rate of disappearance of CO in the gas is given by $\frac{dx}{dt} = -\text{const.}$ $(CO)^2(O_2)$, the rates of burning CO in the two cases given are (1) $4 \times (0.5)^2 = 1.00$; (2) $7 \times (0.4)^2 = 1.12$.

Thus the net velocity of combustion in the second case is considerably greater—with more oxygen. It would take an almost impossible rise in the CO percentage in the second case to neutralize the effect of 75 per cent more free oxygen. In such calculations care must be taken to include the volume of the steam gas present in the 100 per cent total (not the 100 per cent total of the Orsat analysis). This volume can be roughly calculated, and is considerable in percentage and very variable.

It must be constantly borne in mind that calculations of velocity reactions based on the laws of mass action are liable to be seriously in error owing to disturbing side reactions, catalysis, etc.; but probably less is to be feared here with simple gases at high temperatures than with more complex substances at ordinary temperatures. At any rate, these laws of mass action are a very valuable guide in such problems, and if the facts do not fit proved formulas well we have applied too little theory; some refining corollaries must be added.

On page 61 is given a calculation based on actual data obtained, and the conclusion is reached that the velocity of combustion decreases enormously from the surface of the fire to the rear of the combustion chamber, where it is relatively very small; the practical application is that little is to be gained by adding further length of smooth combustion chamber, which would be commercially as poor an investment of capital as to add to the length of a Corliss engine cylinder and stroke; we must resort to thorough mixing.

[a] The sign $\rightleftharpoons$ indicates that a chemical reaction and a reversing decomposition are going on side by side. The composition of the mixture changes according as combination or dissociation is the more rapid.

The question may arise, How are we to treat cases in which more than one combustible gas is present? Simply by adding the two effects together, as when we say that the pressure of a mixture of gases on the walls of a containing vessel is the sum of the pressures of the constituent gases; the two reactions go on independently side by side. Care must be taken not to add these velocity products without having first multiplied each by its proper reduction factor, which for most substances is imperfectly known at present for high temperatures. For the present, therefore, it is not feasible to get an expression for the comparative total velocities of combustion of all constituents taken together at several points along the flame.

Fig. 31 (p. 51) presents an excellent illustration of decrease of completeness of combustion because of decreasing oxygen mass action.

"Furnace efficiency" should more correctly be called "per cent of completeness of combustion," inasmuch as furnaces are usually fixed in size and shape, and so exert about the same mixing effect in all cases.

In the commercial combustion of fuels, where speed of coal consumption is important, so as to get high capacity, the operator must determine whether he will be most benefited by high temperatures or by a close approach to perfection of combustion. If he must put the heat into material at a high temperature, as in melting pig iron or clinkering cement, he must cut down the air supply even at the cost of a large fall in completeness of combustion due to decreased oxygen mass action, so as to have the temperature of the gases as far as possible above that of the material to be worked. If the temperature of his material is low, as is the water in a boiler, it will not make much difference how much air he uses so far as heat absorption is concerned, within reasonable limits; and larger porportions of air mean larger oxygen mass action and more complete combustion. As a general rule the air supply per pound of fuel must be decreased, at a sacrifice of completeness of combustion, when the temperature of the material into which heat is to be put is high.

The only method of alleviating this condition is by making combustion chambers longer, or, much better yet, by putting some fire-brick mixing structure in the path of the gases. As such a structure is damaged more by high than by low temperatures, it should be placed in the first part of the path of the gases to be mixed.

The most economical burning of various fuels for various purposes is largely dependent on proper adjustment of oxygen mass action, assisted by good stream-mixing structures.

DIMENSIONS OF BOILERS AND SETTINGS.

The following is a statement of the dimensions of the boilers and settings at the fuel-testing plant:

Dimensions of Heine water-tube boilers and settings used in steaming tests.

Length of drum	feet	$21\frac{7}{12}$
Inside diameter of drum	inches	42
Number of tubes		116
Internal diameter of tubes	inches	3.26
Outside diameter of tubes	do	3.5
Length of tubes exposed	feet	$17\frac{7}{12}$
Plain grate:		
Width of furnace	do	6.16
Length of furnace	do	6.58
Mean height of furnace	inches	26
Air space	per cent	45
Area of grate surface	square feet	40.55
Rocking grate:		
Width of furnace	feet	6
Length of furnace	do	6.07
Area of grate surface	square feet	36.4
Depth of ash pit below grate	inches	25
Height of stack above grate	feet	113.25
Diameter of stack	inches	37.5
Area of gas passages:		
Stack	square inches	1,104
Draft passage over bridge wall	do	888
Aggregate between lower entrance tubes to boiler	do	1,070
Aggregate between tubes in boiler	do	1,612
Aggregate between upper tubes from boiler	do	640
Area of water-heating surface:		
Tubes	square feet	1,897
Water legs	do	91
Shell	do	43
Total	do	2,031
Superheating area		None.
Total water space	cubic feet	287
Steam space	do	73
Ratio of heating surface to grate surface		50.1 to 1
Ratio of smallest draft area to grate area		1 to 9.1

The boilers were erected by the Heine Boiler Company, and were similar to those in commercial use.[a] When the water stood at 3 inches in the gage glass, boiler No. 1 contained 16,850 pounds of water, and boiler No. 2, 16,755 pounds of water, at 75° F. Each inch of water, as shown by the glass, represented 340 pounds in the boiler. This figure was determined by calibrating the boilers with cold water at about 75° F., by noting the height of water in the gage glass as the water was drawn from the blow-off and weighed.

[a] For further description of apparatus see Prof. Paper U. S. Geol. Survey No. 48, 1906, pp. 302-314.

TRUE BOILER EFFICIENCY.

In confirmation of the ideas on boiler efficiency and heat absorption advanced in this study, and of the probability of being able so to construct boilers as to evaporate several times as much water per unit of heating surface, the boiler division has recently begun some accurate experiments on heat transmission through the tubes of

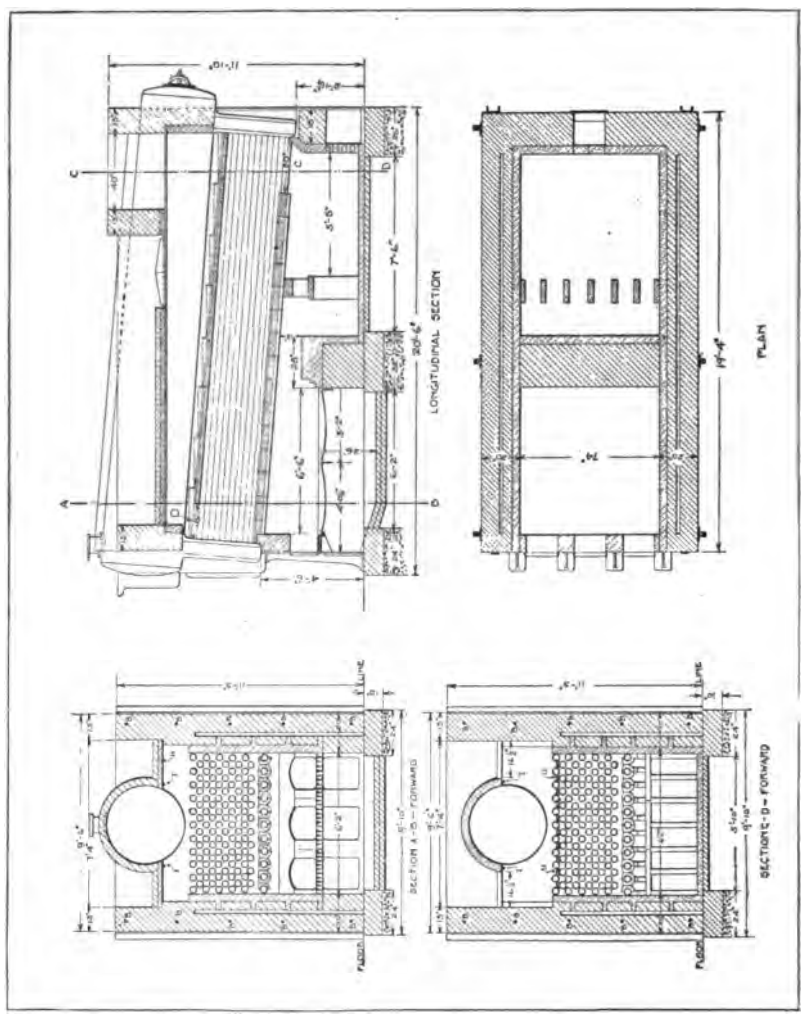

FIG. 76. Dimensions and details of boiler setting.

small multitubular boilers and finds that the results answer to Professor Perry's theory very closely.

An account of the first few experiments will be found in a paper read by Prof. L. P. Breckenridge before the Western Society of Engineers, Chicago, March 20, 1907.

GENERAL CONCLUSIONS.

All the tests that are discussed in this bulletin were made under a Heine boiler with a hand-fired furnace. The principal object of these tests was to determine the relative value of coals for steaming purposes. With this in view each coal was burned to its best advantage for hand firing.

All the tests were made at about the rated capacity of the boiler, carrying a steam pressure of about 80 pounds. The average length of a test was about ten hours. The only variable conditions were thickness of fire and intensity of draft.

While the average efficiencies are fairly high, better efficiency could be obtained with furnaces and other conditions more especially adapted to particular coals. The average efficiency obtained at the fuel-testing plant is about 10 per cent higher than is obtained in good commercial plants. This is true for all coals.

The efficiency used as a basis for comparison of coal tests under a boiler is code item 72*. This is the ratio of the heat carried away in the steam to the calorific value of the "combustible." In determining the amount of "combustible" burned it was considered that the coal which fell through the grate was never fired. This efficiency 72* is the product of boiler and furnace efficiencies.

Per cent of completeness of combustion is the ratio of heat evolved in the furnace to the potential heat in the coal ascending from the grate.

The efficiency of the boiler proper is the ratio of the heat absorbed by the boiler to the heat evolved in the furnace. Efficiency 72* is not commonly subdivided into furnace and boiler efficiency on account of the difficulty of determining the actual heat evolved in the furnace.

The true boiler efficiency is the ratio of the heat absorbed by the boiler to the heat available for absorption. This is the true measure of the ability of a boiler to absorb heat.

Inasmuch as efficiency 72* is the product of furnace and boiler efficiency, it increases with an increase of furnace efficiency, which means that efficiency 72* is higher with coals which are more easily and completely burned. Except in extreme cases it is very little affected by the temperature of combustion. High CO_2 content in the gas analysis is not a definite indication of high efficiency, although some high 72* efficiencies were obtained with high CO_2 content in the gas. The best efficiencies of tests recorded in this paper were obtained with about 10 per cent of CO_2. High CO is always an indication of low 72* efficiency. It does not by itself account for all of the incomplete combustion, but merely indicates poor conditions in the furnace. The other combustible gases which probably pass up the stack, though occurring in very small quantities, will account for heat loss many times as great as the CO loss.

The true boiler efficiency (E_4) is not of constant value in commercial boilers, but varies somewhat with temperature of combustion and capacity. This variation with temperature is due to the heat absorbed by radiation from the fire and the hot brick walls. To increase capacity there must be a proportionate increase in temperature difference between the first layer of water and the film of gas adhering to the tube. Since the temperature of the water is in most cases constant, the temperature of the adhering film of gases will be raised and the flue gases will leave the boiler at a higher temperature.

In general the efficiency is affected by the formation of soot and scale on the heating surface and by defective circulation of water in the boiler. These conditions cause poor absorption of heat and higher flue-gas temperature.

The rate of combustion is affected by the chemical composition of the coal, the size of the coal, the intensity of the draft, and to some extent by the thickness of the fire and the formation of clinker. Bituminous coals high in "volatile matter" burn more quickly than those high in "fixed carbon." Coals ranging in size from one-fourth inch to 1½ inches burn much more rapidly than either very small or very large sizes. This is undoubtedly due to a better distribution of air with these sizes. Fine coal, the formation of clinker, and thick fires hinder the passage of air and reduce the rate of combustion. By increasing the draft, more air is drawn through the fuel bed, causing the coal to burn more rapidly.

With higher rates of combustion less air is used per pound of combustible, the temperature of combustion rises, the gases pass through the boiler faster, and after a certain rate of combustion is reached black smoke is produced. Capacity varies almost directly with the rate of combustion. Extremely high or low rates of combustion reduce efficiency.

The presence of ash in dry coal up to about 15 per cent has very little effect on efficiency and capacity. Above this percentage, however, the efficiency drops.

Moisture reduces efficiency and capacity, perhaps, by hindering combustion.

The presence of sulphur in coal is not detrimental to the value of coal as fuel for steaming purposes except where it exists in certain combinations with other constituents of the ash so as to form fusible clinker which may adhere to the grate.

If there are no other reasons for washing coal than for efficient burning, coal need not be washed, as the efficiency of the furnace and boiler are not increased by washing except with coals of high ash or considerable free pyrites. Washed coal can usually be burned at a higher rate of combustion. The washing of coal does not decrease the per cent of black smoke produced.

Most coals when briquetted can be burned at a higher rate of combustion. As a rule briquetted coals burn with little or no smoke.

Bituminous coal should be fired in small quantities every three or four minutes. It is best to fire only on one-half of the grate area at a time. When burning bituminous coal, up to a medium rate of combustion, the production of smoke may be entirely avoided by leaving the furnace doors partly open for a short time immediately after firing. The best thickness of fire ranges from 5 to 10 inches, varying with the intensity of draft of 0.5 to 0.7 inch under the stack damper.

Most of the eastern semibituminous coals, especially the small sizes, cake badly in the fire. When using these coals the fire must be raked frequently. Coal of this class can be fired every five or six minutes and more can be fired at a time than of bituminous coal. Either the spreading or alternate method of firing may be used. Owing to its tendency to crumble, coal of this class usually reaches the boiler room as fine as slack, which reduces its value as a steaming coal. It can be improved for steaming purposes by briquetting.

Good results can be obtained with lignites if a difference of draft of 1½ to 2 inches of water is carried between the ash pit and the stack. With this draft these fuels may be fired in large quantities every six or eight minutes, the spreading method of firing being used. Rocking grates may be used to good advantage in burning lignites.

For hand firing a furnace with a tile roof and large combustion chamber containing good mixing structures is well adapted for burning bituminous and lignitic coals. The mixing structures cause resistance to the passage of furnace gases, and consequently a higher stack draft must be carried to maintain capacity.

COMMERCIAL CONSIDERATIONS.

General.—Inasmuch as the boiler plant is at present the expensive portion of a steaming outfit, and as it probably is possible to cut its cost down to a fraction of the present cost and at the same time obtain a higher efficiency, it is felt that there is good ground for anticipating an enormous improvement in the production of steam power within the next few years. If so, it will not be the first time that a new arrival in a field has spurred on older forms of enterprise to a higher prosperity than they ever dreamed of before. The competition of the gas engine may be the best thing that ever happened to steam engines and turbines.

The statements, theories, and proposals made in this study are widely scattered and may not have been plain because they are mathematically involved. For this reason a short summary will be

made here of the possibility of so improving the system of working steam-turbine plants that they may be permanently kept above commercial competition from gas-producer and engine plants in large powers. Of course there is little doubt that a great field immediately awaits the gas engine in smaller plants, say under 5,000 horsepower. All these suggestions are tentative only.

Boilers.—The authors see no reason why boilers can not be constructed, and probably operated with entire satisfaction, which will produce about ten times the amount of steam now obtained per square foot of heating surface, and with no difficulty in obtaining dry steam. The efficiency from coal to steam should easily be made considerably higher than that of a good performance of to-day. Such a plant would require only a fraction of the present investment in steam plants, buildings, and real estate. Perry states in his book, The Steam Engine and Gas and Oil Engines, that he thinks boilers should be made to do ten and possibly twenty times the work they do at present.

Furnaces.—It will probably be found on attempting this reduction of dimensions and cost that the limit will be not in the boiler as such, but in the combustion chamber. Burning a large amount of coal on a small grate area is largely a question of draft and continual riddance of ash, but the rate of travel of gases through a combustion chamber is dependent, practically, only on the amount of carbon burned per unit of time, the rate being about the same no matter what the air supply per pound of carbon. As combustion chambers are now constructed for western coals they are too small, but "small" is a word not to be understood in this connection as referring to volume or length alone. By a "small combustion chamber" is meant a chamber in which either the time spent by the gas in traveling from the front to the rear of the boiler is short or the mixing devices are inefficient or absent. In the discussion of mass action it was stated that mere length of combustion chamber counts for little—that mixing is what counts—and thus there is a possibility of enormously increasing the efficiency of a combustion chamber as a burner of volatile matter. Effort in completing a steam-generating outfit of small dimensions must be largely concerned with the construction of a combustion chamber containing many gas-mixing appliances.

Turbines.—The work on turbines is provisional only, but it is believed that all the assumptions made are on the side of safety; that is, that the over-all efficiency of the turbines working with high superheat and low pressure would probably be greater than estimated.

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GLOSSARY.

ABSOLUTE TEMPERATURE. The temperature of a substance reckoned from that temperature—461° below the zero on the Fahrenheit scale and 273° below the zero on the centigrade scale—at which all heat is supposedly absent.

AIR-DRIED COAL. A term applied to coal that has been prepared for chemical analysis. The coal is dried at a temperature somewhat above that of the room in which it is to be analyzed, in the atmospheric conditions prevailing in the room, so that the sample will not vary in weight while being handled. No coal has a constant air-drying loss, since its loss in weight varies according to conditions, such as size of coal analyzed, air currents, and weather conditions. Air-drying results are of value only to the chemist who figures them back to coal as received and to dry coal.

AVAILABLE HEAT. The portion of the heat supplied to the boiler over and above the amount required to raise the gases from atmospheric to steam temperature.

AVAILABLE HYDROGEN. The excess of hydrogen in coal over and above that which is required to unite completely with the oxygen in the coal to form water (H_2O). It is found by subtracting one-eighth of the total oxygen from the total hydrogen.

AVOGADRO'S LAW. The temperature and pressure being the same, the number of molecules in a unit volume is the same for all gases.

BAFFLE. A term applied to partitions designed to change the course of moving gases in the combustion chamber or among the boiler tubes.

BASE VALUES. A term used to designate the abscissa value of any point on a curve—that is, the horizontal distance of that point from the left side of the chart.

BLACK BODY. A term used to designate a hollow body whose walls are all at the same temperature. If an extremely small hole were made in such a body, heat would be radiated through the hole in proportion to the difference of the fourth powers of the absolute temperatures of the black body and the surrounding objects.

BOLTZMANN AND STEFAN'S LAW. *See* Stefan and Boltzmann's law.

BRITISH THERMAL UNIT. That quantity of heat which is required to raise the temperature of 1 pound of pure water through 1° F. at or near 39.1° F., the temperature of maximum density of water. The abbreviation B. t. u. is used in this volume.

CAKING COAL. A term applied to coal which fuses together when burning—a coal that is not free burning.

CAPACITY. A term rather loosely used to denote the percentage of steam made, taking as the basis (100 per cent) the rated evaporation designated by the boiler builder.

CARBON—AVAILABLE-HYDROGEN RATIO. The total carbon content of coal divided by the available hydrogen (q. v.).

CARBON, FIXED. *See* Fixed carbon.

CARBON—HYDROGEN RATIO OF DRY COAL. The total carbon content divided by the total hydrogen content.

CARBON—HYDROGEN RATIO OF COAL "AS FIRED," OR "AS RECEIVED" (MOIST COAL). The total carbon content divided by the total hydrogen content, including the hydrogen of the free moisture present.

CATALYZER. A substance whose presence, among the substances participating in a chemical reaction, hastens or retards the speed of the reaction, although the nature and total amount of catalyzer present is always the same at the end as at the beginning of the reaction, so far as can be detected.

CELLULOSE. A substance represented chemically by the expression $C_6H_{10}O_5$. It is the basis of wood structure, excluding a slight amount of mineral ash in the cell walls.

CLINKER. A term used herein to designate the more or less molten portions of ash (including some carbon) drawn from the grate and ash pit.

CO. Abbreviation for carbon monoxide.

CO_2. Abbreviation for carbon dioxide.

COAL, AIR-DRIED. *See* Air-dried coal.

COAL, DRY. *See* Dry coal.

COAL, FREE-BURNING. *See* Free-burning coal.

COMBUSTIBLE. A loose expression and misnomer for the phrase "coal free from moisture and ash," sometimes called "pure coal." The pounds of "combustible" used in every steam test have been computed in two ways, as follows:

1. Item 30: Obtained by subtracting from the total pounds of dry coal fired the pounds of ash and combustible drawn out of the ash pit and through the fire doors in cleaning the fire.

2. Item 30*: The weight of the coal fired is corrected for moisture and ash as given by the proximate analysis, thereby giving the pounds of "combustible" fired. From this amount is subtracted the pounds of "combustible" lost in the refuse, giving the total pounds of "combustible" actually ascending from the grate during the test.

Two efficiencies have been figured from these weights of "combustible"—items 72 and 72*.

In this bulletin there are many references to "code item 72*." In reality there is no such item. This 72* item is the one given in the code as item 72, and is the comparable efficiency, because with different grates different amounts of coal might drop into the ash pit and in figuring 72* corrections have been made for this loss. (*See* 72* under "Computations of a steaming test," p. 151.)

Whenever the word "combustible" in this bulletin is in quotation marks it means "coal free from moisture and ash." Quotation marks are employed because the word used in this sense is a misnomer, inasmuch as the oxygen and nitrogen, and perhaps part of the sulphur, do not burn.

COMBUSTION CHAMBER. Strictly, the entire space between the surface of the fuel bed and the area at which the gases enter the boiler; term usually applied, however, to designate the space between the bridge wall and that area.

CONDUCTION. The process of transferring heat by direct contact; as when heat travels along a rod, or from a hot stove lid to a flatiron resting on it.

CONVECTION. The addition to, or removal from, a body of heat, by gases or liquids circulating in direct contact with the body; as the removal of heat from a steam radiator by the circulation of air.

CONES, SEGER. *See* Seger cones.

DISSOCIATION. The state of separation of the molecules of a substance into two or more parts. A term used herein to denote effects due to high temperatures.

DRY CHIMNEY GASES. In all calculations in this bulletin this term includes CO_2, O_2, CO, and N_2 gases.

DRY COAL. Coal which has been dried in a very finely powdered condition for one hour at a constant temperature of 105° C. In the expression "B. t. u. per pound of dry coal as fired," however, the "dry coal" is computed from a determination of the moisture in the coal sample.

EFFICIENCIES:

Boiler and grate ("over-all") efficiency, code item 73, denoted by E_1, is the ratio of the heat absorbed by boiler to the potential heat of dry coal fired.

Boiler efficiency, code item 72*, denoted by E_2, is the ratio of the heat absorbed by the boiler to the potential heat of combustible ascending from grate. The combustible in this item is equal to the total dry coal fired, minus the ash by analysis of dry coal, minus the combustible in refuse.

Boiler efficiency, code item 72 (seldom referred to in this bulletin), is the same as 72*, except that the combustible is taken to be equal to total dry coal fired minus the total refuse determined by actual weighing, this total refuse being combustible and ash.

Furnace efficiency, or *per cent of completeness of combustion*, denoted by E_3, is the ratio of the heat actually evolved in the furnace to the potential heat of the combustible ascending from the grate.

EFFICIENCIES—Continued.

True boiler efficiency, denoted by E_4, is the ratio of the heat absorbed by the boiler to the heat in the gases which is available to the boiler, counting only that part of the heat in the gases as available to the boiler which remains after subtracting from the total heat actually generated the amount which is used in heating the gases from atmospheric to steam temperature.

Boiler efficiency corrected, denoted by E_5, is the ratio of the heat absorbed by the boiler to the heat actually evolved in the furnace.

Thermodynamic furnace efficiency is the ratio of the heat made available to the boiler to the potential heat of coal fired.

Thermodynamic efficiency of boiler is the ratio of the heat made available for engine or turbine to the heat available to the boiler.

EMPIRICAL FORMULA. A formula expressing the actual relations between two or more variables and constants, but not founded on known laws. Cf. "Rational formula."

ENDOTHERMIC. An adjective describing a chemical reaction which can take place only by absorbing heat from the surroundings or by reducing the temperature of the reacting matter. The opposite of exothermic.

EXOTHERMIC. An adjective describing a chemical reaction which evolves heat. The opposite of endothermic.

FIXED CARBON. A term applied to that portion of the carbon in a coal left after the "volatilization" process of the proximate analysis. It is obtained by subtracting from 100 the percentages of ash, moisture, and volatile matter.

FREE-BURNING COAL. A term applied to coal which when thrown in the fire burns without the separate pieces of coal fusing together. A noncaking coal.

"FREE" MOISTURE. Moisture which is driven off from coal when subjected to a temperature of 105° C. (221° F.) for one hour.

GRAM MOLECULE. An amount of a substance, in grams, numerically equal to the molecular weight of the substance. For instance, a gram molecule of water is 18 grams, the molecular weight of water being 18 (2 of hydrogen and 16 of oxygen).

HEAT, AVAILABLE. *See* Available heat.

HOOD. The inverted funnel, usually about 4 feet high, between the top of the brick setting and the bottom of the cylindrical smokestack. The flue temperatures and gas samples are taken at the top of the hood, and the stack damper is just above this point.

HYDROGEN, AVAILABLE. *See* Available hydrogen.

HYDROCARBON GASES (HYDROCARBONS). Gases which are distilled from coal when it is heated. They are high in heating value, approximately 1½ times as high in B. t. u. per pound as pure carbon. They usually occur in three forms, expressed by the formulas: C_nH_n, C_nH_{2n}, and C_nH_{2n+2}.

IGNITION TEMPERATURE. The ignition temperature of a substance is that temperature to which it must be raised in the presence of oxygen to cause the two to unite by combustion. This temperature is rather indefinite, as extremely slow union begins far below the point of rapid union. For any one substance there are generally two temperatures, within perhaps 200° F. of each other, at the lower of which the rate of combustion is inappreciable and at the higher of which it is almost infinite.

KINETIC THEORY OF GASES. This theory postulates that gases consist of immense numbers of individual molecules moving among each other with enormous velocities. The sum of the molecular impacts against the sides of a containing vessel constitutes the pressure of a gas. Raising the temperature of a gas increases the molecular speed, and consequently the force of impact.

MASS ACTION, LAW OF. The speed of a chemical reaction is proportional to the product of the weights of reacting substances present, in unit volume, the weight of each substance being expressed in gram molecules.

MOISTURE, "FREE." *See* "Free" moisture.

O_2. Abbreviation for oxygen (one gaseous molecule).

ORSAT APPARATUS. An instrument for determining the percentages of carbon dioxide, oxygen, and carbon monoxide by absorbing them successively in certain solutions. (See text-books on gas analysis.)

POTENTIAL HEAT. A term applied to the heat in coal as determined by a calorimeter.

PROBABILITY CURVE. The graphic plotting of a certain mathematical equation expressing the likelihood of a quantity being more or less different from what it "ought" to be. (See p. 158.)

PROXIMATE ANALYSIS OF COAL. An empirical method of determining the percentage of "free" moisture, of "volatile matter," of "fixed carbon," and of ash in coal. The method of determination varies somewhat with different chemists.

PYROMETER. An instrument for measuring high temperatures.

RADIATION. The process of transferring heat through space from one body to another without the aid of tangible substance—for example, the transfer of heat from the sun to the earth.

RATIONAL FORMULA. A formula deduced from fundamental laws, as of physics. Cf. "Empirical formula."

REFUSE. Clinker, ash, and unconsumed coal taken from the ash pit and pulled out of the furnace when cleaning fire.

SEGER CONES. Small pyramids made of various chemicals variously mixed. The temperatures of softening of the different cones are fairly well known. Several of them are put into a furnace in a row, each having a melting point intermediate between its neighbors. By watching the curling over of the tips one can form a fairly correct estimate of the average temperature.

STEFAN AND BOLTZMANN'S LAW. The amount of energy radiated by a black-body surface to another body is proportional to the difference of the fourth powers of their absolute temperatures.

STRAIGHT-LINE FUNCTION. A value changing directly or inversely with a variable, so that if simultaneous values are plotted on coordinate paper the points would lie in a straight line.

TEMPERATURE, ABSOLUTE. *See* Absolute temperature.

TEMPERATURE, IGNITION. *See* Ignition temperature.

TEMPERATURE GRADIENT. As used in this bulletin, any continuous change of temperature along a body actively conducting heat.

ULTIMATE ANALYSIS OF COAL. A chemical analysis so made as to give, in percentages, the amounts of carbon, hydrogen, oxygen, nitrogen, and ash in a dry coal. The sulphur is separately determined.

"UNACCOUNTED-FOR LOSS." That percentage of the potential heat of a combustible which remains after deducting all the known expenditures of heat.

VELOCITY. A term loosely applied to the speed of a chemical reaction—for example. combustion. It is proportional at any instant to the rate of formation of new substance by the reaction.

VOLATILE MATTER FROM PROXIMATE ANALYSIS, or "volatile combustible matter," as it is often incorrectly termed, is the mixture of gases, together with some particles of carbon, driven off when a sample of finely ground coal is heated in a closed vessel. This is an arbitrary determination, dependent on the operator and the conditions under which it is made. A committee from the American Chemical Society has suggested a method of volatilization which is generally followed. This method gives fairly concordant results when the same operator, using the same apparatus, makes duplicate determinations on the same sample of coal.

VOLATILE CARBON. A name given to that part of the carbon in coal which is expelled in the process of volatilization by the "standard method" of proximate analysis. It exists in the "volatile matter" resulting from distillation, largely in combination with hydrogen as gaseous hydrocarbons.

WATER OF COMPOSITION. A fictitious value determined by uniting the total oxygen in dry coal with such a part of the hydrogen as would be required to form water.

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